The Handbook of Environmental Chemistry 79

Series Editors: Damià Barceló · Andrey G. Kostianoy

Abdelazim M. Negm
Sommer Abdel-Fattah *Editors*

Grand Ethiopian Renaissance Dam Versus Aswan High Dam

A View from Egypt

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Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geoecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry*, there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry*, the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of Environmental Chemistry* provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Preface

This volume came into conception to highlight the great challenges facing Egypt due to the severe shortage of water which will be even more pronounced due to the negative impacts resulting from the full operation of the Grand Ethiopian Renaissance Dam (GERD) at the border of Ethiopia with Sudan. This unique volume is authored by Egyptian Scientists and researchers to present the results and findings of their research work and the related state of the art connected to the topic. The views presented in the book are the result of extensive scientific efforts and not personal view. It should be stated that the presented views in this book are not necessarily the views of the Egyptian government. Any chapter included in this book reflects the personal view of the author(s) based on the involved assumption and the conducted investigations.

The volume consists of 7 parts and comprises 20 chapters written by more than 30 authors. Part I is an introduction to the volume and consists of one chapter titled "An Overview of Aswan High Dam and Grand Ethiopian Renaissance Dam." The author presents a general overview and the basic available data of both dams. Also, the major advantages and disadvantages of each are listed.

Part II is titled "Importance and Environmental Impacts of AHD" and presents a review of both positive and negative environmental impacts of the AHD. It consists of two chapters. The chapter titled "Environmental Impacts of AHD on Egypt Between the Last and the Following 50 Years" provides a brief overview of both positive and negative environmental impacts of the AHD, while the chapter titled "Importance of Aswan High Dam to Egypt" presents in some detail the positive impacts of the AHD on Egypt and Egyptian Society and how the AHD shifted Egypt to a new era.

Part III consists of four chapters and deals with "Modeling the Impacts of GERD on AHD and Its Downstream" due to the fact that the GERD is still under construction and modeling is the only way to anticipate and predict the impacts of the dam on the AHD and the downstream area. The chapter titled "Stochastic Investigation of the GERD-AHD Interaction Through First Impoundment and Beyond" discusses the different scenarios of the operation and the resulting interaction of GERD-AHD. In the chapter "Impacts of Constructing the Grand Ethiopian Renaissance Dam on the Nile River," the authors discuss the hydrological and environmental impacts of GERD on Egypt and Sudan. The chapter also aims to identify, predict, and analyze the impacts of the GERD on the Nile River stream flow. The results of modeling a variety of operation rules that minimize the harm to Egypt and maximize the power generation capacity of Ethiopia are presented in the chapter "Model-Based Optimization for Operating the Ethiopian Renaissance Dam on the Blue Nile River." The last chapter in this section entitled "GERD Failure Analysis and the Impacts on Downstream Countries" is devoted to analyzing the expected impacts on both Sudan and Egypt if the GERD fails due to a severe earthquake or any other reasons.

Part IV consists of two chapters and is an overview of the environmental impacts of the GERD on AHD Lake and the associated socioeconomic impacts of constructing the GERD on Egypt's agriculture and the rural poor in Egypt. The first chapter titled "Environmental Impacts of the GERD Project on Egypt's Aswan High Dam Lake and Mitigation and Adaptation Options" presents the expected environmental impacts of the GERD on Egypt and discusses the options for possible mitigation and adaptation, while the chapter titled "The Grand Ethiopian Renaissance Dam, Agriculture and the Rural Poor in Egypt" analyzes and presents the socioeconomic impacts of the GERD on the agricultural and the rural poor in Egypt based on a macro-level assessment.

Part V consists of three chapters and is an assessment of the sediment of the AHD reservoir. The first chapter is titled "Assessment of Sediment Deposition in High Aswan Dam Reservoir During 50 Years (1964–2014)." The author presents an overview and assessment of the AHD Lake sediment for the period from 1964 to 2014. The chapter titled "Evaluation of Merowe Dam's Effect on the Accumulated Sediment in Lake Nubia, Sudan Using RS/GIS" discusses how Merowe Dam impacts the sediment accumulation in Lake Nubia to account for or ignore this impact while investigating and evaluating the impacts of the GERD on AHD Lake. The third chapter in this section is titled "Impacts of GERD on the Accumulated Sediment in Lake Nubia Using Machine Learning and GIS Techniques." It discusses a methodology to simulate the impacts of GERD operation and the shortage of incoming water with low sediment (Hungary water) on the accumulated sediments in Lake Nubia and its redistribution over AHD Lake. It also predicts the new pattern of sediment over Nubia Lake until the year 2060.

Part VI consists of three chapters dealing with the ways of maximizing the benefits of AHD reservoir and its sediment. The chapter "Dredging the Clays of the Nile: Potential Challenges and Opportunities on the Shores of the Aswan High Dam Reservoir and the Nile Valley in Egypt" presents a methodology to evacuate AHD Lake from the accumulated sediments and use it in agricultural and industrial activities. In the chapter "Community Development by De-silting the Aswan High Dam Reservoir," the authors discuss how Egypt can develop new communities based on the resources of AHD Lake including the sediment. On the other hand, the chapter titled "Harvesting the Skies of Egypt: An Option to Recover the Evaporation Losses from the Aswan High Dam Reservoir" presents a proposed framework to enable Egypt to harvest the evaporation from AHD Lake and use in arid lands for human activities.

Part VII consists of four chapters that discuss international aspects related to the construction of AHD and GERD. The chapter "Impact of the International Context on the Political and Legal Dimensions of the Aswan High Dam (1952–1960)" presents a comprehensive overview of the international and legal dimensions of the AHD and the dialogue between the different national and international entities during the period from 1952 to 1960. In the chapter "Continuous Dispute Between Egypt and Ethiopia Concerning Nile Water and Mega Dams," the author discusses the aspects of the dispute between Ethiopia and Egypt since the early beginning of the idea of constructing the border dam until present. The chapter "The Grand Ethiopian Renaissance Dam and the Ethiopian Challenge of Hydropolitical Hegemony on the Nile Basin" presents the hydropolitics and the efforts of Ethiopia to gain hydropolitical hegemony on the Nile Basin regardless of the no harm rule of the international rivers, although several ill effects are evaluated and stressed in many local and international studies. The last chapter in this section which is titled "Impact of the Grand Ethiopian Renaissance Dam (GERD) on Gezira Groundwater, Sudan" discusses a methodology to study the effects of the GERD on the groundwater of Gezira zone in Sudan via modeling processes. The last chapter in this volume is the conclusions chapter which presents an update of the most recent findings and also presents the most significant conclusions and recommendations of this volume.

Special thanks are due to the Springer team who largely supported the authors and editors during the production of this volume. Thanks should be extended to all the authors who contributed to this volume; without their efforts and patience, it would not have been possible to produce this unique volume on the GERD and AHD.

Zagazig, Egypt
Hamilton, ON, Canada
28 April 2018

Abdelazim M. Negm
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An Overview of Aswan High Dam and Grand Ethiopian Renaissance Dam

Abdelazim Negm, Mohamed Elsahabi, and Mohamed Salman Tayie

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Abstract Egypt is facing many challenging since the year 2011. At the top of these challenges, the freshwater scarcity at the same of the increasing demand of freshwater for the rapid growth of populations and consequently the increasing demand for food. The construction of Grand Ethiopian Renaissance Dam (GERD) imposed additional challenges to Egypt due to the expected harm to all sectors in Egypt particularly the agricultural sector which consumes about 80–85% of the freshwater. Therefore, this chapter introduces the basic information GERD and AHD. Also, the major environmental impacts and benefits of GERD compared to Aswan High Dam (AHD) are presented as an introduction to this unique volume about GERD and AHD in the series titled “Handbook of Environmental Chemistry.”

Keywords Aswan High Dam, Benefits, Grand Ethiopian Renaissance Dam (GERD), Hydropower, Impacts

1 Overview of the Nile River

The Nile River, which is an international river, is a major north-flowing river in northeastern Africa. The Nile water resources are shared by 11 countries, namely, Tanzania, Uganda, Rwanda, Burundi, the Democratic Republic of the Congo, Kenya, Ethiopia, Eritrea, South Sudan, Sudan, and Egypt (see Fig. 1).

In principle, the Nile is the supplied Egypt with almost 97% of its water resource. Therefore, without the Nile, Egypt will die. It is well known that almost all the cultural and historical sites of ancient Egypt are found along its riverbanks.

The Nile River receives its flows from three main distinct watersheds [2]. These are the Equatorial Lake Plateau in the south, the Bahr el-Ghazal in the center, and the Ethiopian Highlands in the east. From the confluence of Atbara River north of Khartoum to the Mediterranean Sea, the Nile receives no effective inflow.

The Nile has two major tributaries, the White Nile and the Blue Nile (see Fig. 1). The White Nile is longer and rises from the Great Lakes region of central Africa, with the most distant source still undetermined but located in either Rwanda or Burundi. It flows north through Tanzania, Lake Victoria, Uganda, and South Sudan. The Blue Nile is the source of most of the water and fertile soil. It begins at Lake Tana and flows into Sudan. The two rivers meet near Khartoum. Figure 1 shows a map of the Nile River basin countries and the Nile tributaries.

The northern part of the river flows almost entirely through desert, from Sudan into Egypt, where civilization has depended on the river since ancient times. Most of the population and cities of Egypt lie along the Nile valley north of Aswan.

Although the Nile is the world’s longest river with a total length of 6,853 km long, its average annual natural flow at Aswan just 84 billion cubic meters (BCM) averaged over the period from 1900 to 1954.

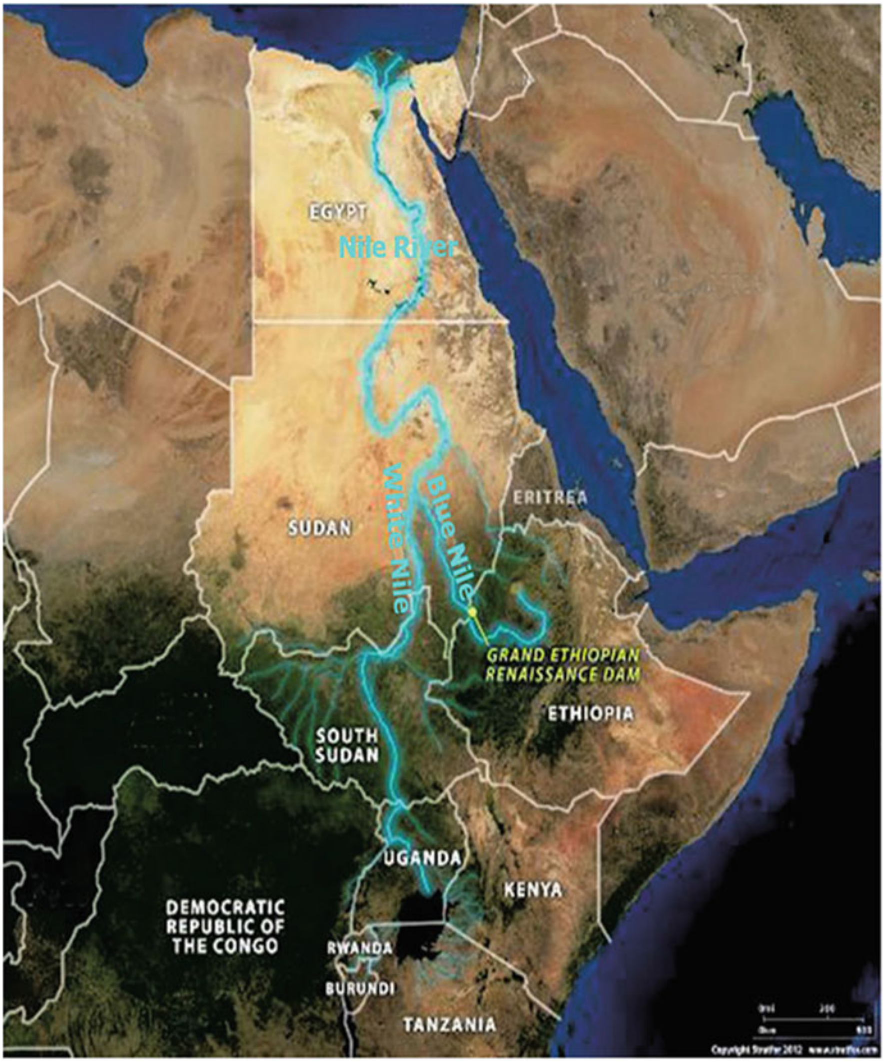

Fig. 1 Nile basin map: countries and tributaries [1]

2 Brief Description of Aswan High Dam

The AHD is a rock-fill dam, completed in 1968 and fully operated in 1972. It is located 17.0 km south of Aswan City [3]. Figure 2 shows a scene for AHD from space.

The Aswan High Dam (AHD) was built not only to control flood but also to achieve other objectives such as satisfying industrial power demand, developing Egypt's agriculture expansion plans, and navigation improvement. Construction of the AHD began in 1960 and completed in 1971. The structure total length is 3,600,

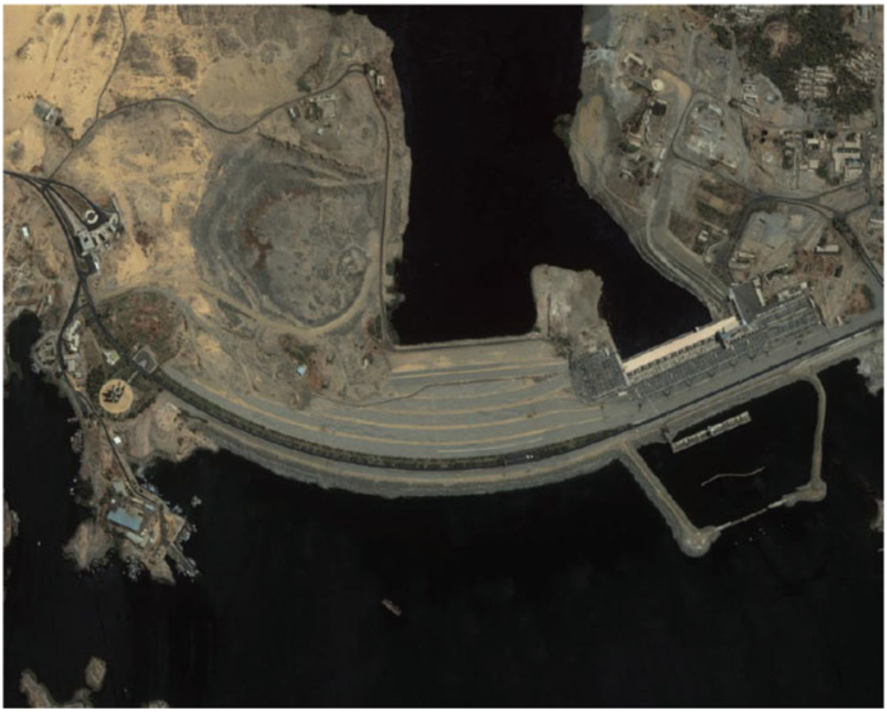

Fig. 2 The AHD as seen from space (Photo courtesy of NASA)

the height is 111 m above the river bed, and the width is 40 m at the crest and 980 m at the base. Its hydropower station capacity is 109 kWh/year [4]. After completion of AHD construction, the dam controls flooding, ensures reliable and regular water supply to irrigated farms along the river, and provides hydroelectric power and water for human consumption and industrial use [5].

The construction steps can be historically summarized as follows:

1960: Start of construction.
1964: First dam construction stage completed, reservoir started filling.
1970: The High Dam completed on 21th July.
1976: Reservoir reached full capacity.

3 Impacts of Aswan High Dam

The overall impacts of the construction of the AHD can be classified into four broad categories: physical, biological, economic, and social [6]. This classification is somewhat arbitrary since many of the impacts are often interrelated and some of them may spawn effects of other types.

Among the main physical impacts of the dam were the following [6]:

- Changes in the level, velocity, and discharge of the flow in the Nile River both upstream and downstream of the dam.
- Increase in groundwater levels due to the introduction of year-long irrigation.
- Causing changes in soil salinity and water logging.
- Causing erosion of the river banks, beds, and delta.
- Causing sedimentation in the river and Lake Nasser.
- Possible earthquakes.
- Reclamation of the desert for human habitat and agriculture.

There were several major biological impacts, which included [6]:

- Implications for fish production.
- Changes in flora and fauna.

Among the economic impacts were [6]:

- Generation of hydropower.
- Increase in industrial activities and industrial diversification, because of the availability of electricity.
- Increase in agricultural land, as well as crop intensification and diversification.
- Impacts on brick-making industry.

There were several social impacts, which included [6]:

- Peace and stability of the country due to increased economic activities and a higher standard of living.
- Eliminating the ravages of floods and droughts downstream of the dam.
- Resettlement issues.

More details about the impacts of the construction of the AHD could be found in [4, 6, 7], and part II of this volume.

4 Aswan High Dam Reservoir

The Aswan High Dam Reservoir (AHDR) (sometimes called Aswan High Dam Lake – AHDL) is considered one of the most important components of the water resource systems in Egypt. It regulates the discharge downstream of the AHD to match the actual water needs for different requirements of the country [3]. Moreover, this lake is considered the main source of freshwater for about 85% of its population [8]. The Aswan High Dam Lake (AHDL) is one of the greatest man-made reservoirs in the world, created after the construction of the AHD. This reservoir extends for 500 km along the Nile River from the southern part of Egypt to the northern part of Sudan. It covers an area of about 6,000 km^2, of which two-thirds (known as Lake Nasser, 350 km) is in Egypt and one-third (called Lake Nubia, 150 km) is in Sudan [3], as shown in Fig. 3. Table 1 gives further characteristics of AHDL.

Fig. 3 Location map of Aswan High Dam, Lake Nasser, and Lake Nubia

Table 1 Characteristics of the Aswan High Dam Reservoir (AHDR) [9]

Characteristics	Values
Max length (km)	500
Max width (km)	12
Maximum depth (m)	110
Mean depth (m)	70
Water volume (billion m^3)	162
Average annual inflow (billion m^3/year)	70
Major water uses	Irrigation, hydropower

Moreover, the AHDL designed storage capacity (162 billion m^3) is distributed as follows [3]:

- 31.6 billion m^3: dead storage between levels of 85 m and 147 m
- 90.7 billion m^3: live storage capacity between levels of 147 m and 175 m
- 39.7 billion m^3: flood control storage capacity between levels of 175 m and 182 m

Furthermore, the AHDL shoreline is very irregular, with numerous side channels known as khors. There are about 85 longer khors, 48 of which are on the east side and 37 on the west side. The mean length of the khors increases downstream from south to north, and all are U-shaped in cross section. Their surface area covers about 4,900 km^2, i.e., 79% of total lake surface, while their volume is 86.4 km^3, i.e., 55% of total lake volume [10].

Lake Nasser Reservoir Nasser is the Egyptian part of the AHDR. It is located between latitudes 22° 00′ 00″ N (upstream the AHD) and the AHD in the north as presented in Fig. 3. Lake Nasser water is a major source used for drinking, irrigation, and domestic purposes in Egypt [11]. Lake Nasser is a large reservoir in the midst of the desert with a large surface area, which leads to high amounts of water loss by evaporation that reaches 10 BCM/year [12].

Lake Nubia is the Sudanese part of the AHDR as given in Fig. 3. It is located between latitudes 21° 02′ 00″ and 22° 00′ 00″ N (upstream the AHD). The southern two-thirds of this Lake are narrow, while the remaining northern part is much wider [13], as indicated in Fig. 4.

5 Brief Description of GERD Project

The GERD "project is located approximately 500 km North West of the capital Addis Ababa, in the region of Benishangul - Gumaz along the Blue Nile. At the end of the works, the Grand Ethiopian Renaissance Dam will be the largest dam in Africa: 1,800 m long, 155 m high and with a total volume of 74,000 million m^3" [14].

This project involves the construction of the "main dam in Roller Compacted Concrete (RCC), with 2 power stations installed at the foot of the dam. The power stations are positioned on the right and left banks of the river and comprise 16 Francis turbines with a total installed power of 6,000 MW and estimated production of 15,000 GWh per year. The project is completed by a 15,000 m3/s capacity concrete spillway and a rock-fill saddle dam 5 km long and 50 m high, both located on the left bank" (https://www.foi.se/download/18.67e0f0be156ecf162a738/1472924291222/FOI+Memo+5492+Nr+9.pdf) [15, 16]. Figure 5 shows the location of GERD project.

Fig. 4 Location of Lake Nubia in Sudan (https://glovis.usgs.gov/)

According to Salini Company [14], the technical data of main dam are:
Grand Ethiopian Renaissance Dam Project

Country: Ethiopia
Client: Ethiopian Electric Power
Total value: € 3,377.05 million
Start of works: December 2010 (announced later in 2011).
Expected duration: 78 months
Height: 155 m
Length: 1,780 m
Excavations: 3,500,000 m^3
Volume: 10,200,000 m^3
Powerhouses (x2)
Right riverbank: 10 Francis turbines, each offering 375 MW
Left riverbank: 6 Francis turbines, each offering 375 MW

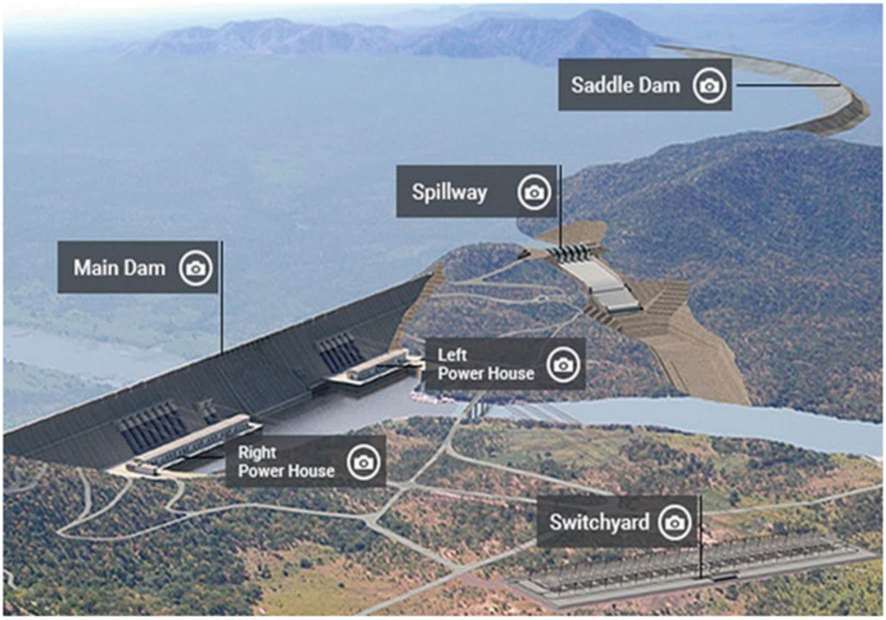

Fig. 5 Location of GERD project, about 20 km from Sudan border and the main components (http://africanleadership.co.uk/ethiopia-gerd-generation-capacity-increases-to-6450-mw/)

Power and Energy

Installed power: 6,000 MW
Generation capacity: 15,000 GWh/year

The technical data of the rock-fill saddle dam are:

Height: 50 m
Length: 5,000 m
Rock-fill volume: 16,500,000 m^3

6 The Historical Development of GERD

6.1 Lakes Border Dam

This was the original name mentioned in the US Bureau study in 1964. It was also known as “Hidasse” Dam. According to the US study, its storage capacity was 11.1 BCM and could be as high as 16.5 BCM. Ethiopia has kept secret its intention to establish the “Border” dam, which was not included in Ethiopia’s 5-year plan or in any official statement. Taking advantage of Egypt’s preoccupation with the events of the January 25 revolution, the Ethiopian newspaper *Addis Fortune* announced on 6th February Ethiopia's intention to establish the dam [17].

6.2 Project X

"Addis Fortune newspaper" announced that the Ethiopian Electric Power Company (EEPCO) had started the construction of an electric project on the Blue Nile, called Project X, considering that the project will be a locomotive for development in Ethiopia in the next phase. No further details than what is known about the "Border" dam were mentioned until it was officially announced on 31st March 2011 in a press conference of the Ethiopian Minister of Water and Energy "Alemayehu Tegenu" who confirmed the previous information. This came only 1 day before the signing of the project contract with the Italian company "Salini" without an international tender for 4.8 billion US dollars [18].

6.3 Grand Millennium Dam

Ethiopia announced the change of project name from Project X to Grand Millennium Dam. The foundation stone was laid the day after the signing of the contract on 2nd April 2011, with higher storage capacity. Meles Zenawi, the Ethiopian prime minister at that time, commented on the designation of the Great Millennium Dam by saying: "It will be Ethiopia's largest dam on the Nile or any other Ethiopian river in the current millennium. It will be at the top of Ethiopian projects. This Dam will move Ethiopia from poverty, which is an addition that is not comparable to the national plan for the expansion of energy production."

6.4 Grand Ethiopian Renaissance Dam

In less than 2 weeks after the project was renamed the Grand Millennium Dam, the name was changed for the third time in the same month. On 15th April 2011, the Ethiopian Cabinet announced the new name of the project to be the Grand Ethiopian Renaissance Dam [19]. Thus, the name of the dam was changed three times in only 45 days, and each time it was a more popular name. Therefore, it was natural that the change in the name of the dam was accompanied by a steady increase in the specifications of the technical project. In terms of the dam storage capacity, it changed from 11.1 BCM, according to the American study, to 62 BCM according to the Ethiopian Minister of Water and Energy. Then it increased to 67 BCM in the statements of the Ethiopian Prime Minister, then to 70 BCM, and finally to 74 BCM in 2012 [20].

7 GERD Benefits, Disadvantages, and the Major Threats to Egypt

The GERD benefits and disadvantages on the regional scale were presented in the chapter "The Grand Ethiopian Renaissance Dam and the Ethiopian Challenge of Hydropolitical Hegemony on the Nile Basin" in relation to the no harm rule and the part II of this volume.

7.1 GERD and the Threat of Egyptian Water Resources

At the Egyptian domestic level, experts and specialists stressed that the dam has great risks on all aspects: water, agriculture, environment, economic, social, and electrical. The details of the dam and its negative effects on Egypt can be identified through the report issued by the Technical Committee for the Dam Assessment, which was issued in May 2013 [21, 22].

Also, studies conducted by the professors of Cairo University, which have been confirmed by international studies, confirm that the expected effects of GERD on Egypt's water security are high and may be disastrous especially during the filling period of the dam. If the filling is synchronized with a flood period below the average, the effects will be catastrophic. Egypt is expected to be unable to get its share of water with a maximum deficit of 34% of the quota (19 BCM) and an average deficit of 20% 11 BCM during the filling period, which extends to 6 years [23]. These impacts are exacerbated as climate changes increase [24].

The filling of the lake behind this dam with this huge volume of water – even if it is estimated that it could happen within 5 years – means deducting 15 BCM each year from the share of Egypt and Sudan. To put more accurately, it will be from Egypt's share only since Sudan's dams (Khashm el-Girba, Rusairis, Sennar, and Marwa) reserve Sudan's share of the water before it reaches Egypt.

If Ethiopia decided to fill the lake in just 3 years, it means deducting 25 BCM per year, which means major destruction to Egypt [25].

GERD preliminary technical studies indicate that the greatest risk in that dam is that it is located on a very rugged slope. Therefore, the probability of its collapse is very high. Moreover, its safety coefficient is not more than 1.5 degrees compared to the High Dam 8 degrees' safety factor. The report of the International Technical Committee concerned with assessing the impacts of the Renaissance Dam, which issued its report in May 2013, confirmed the lack of scientific studies needed for the GERD project, in particular, the apparent imbalance in engineering studies on GERD safety [26, 27].

7.2 GERD and the Threat of the Egyptian Agricultural Sector

Experts point out that the shortage of water coming into Egypt due to GERD would have a negative impact on the size of the agricultural area. 3.5 million feddans are expected to be deprived of agriculture. These effects would have serious environmental and social consequences, most notably of which are [27]:

1. Each shortage of the Nile water by (4–5) BCM is equivalent to destructing million agricultural acres. In turn, this means the displacement of two million families on the streets in addition to the loss of 12% of agricultural production.
2. Reducing areas of water-consuming crops such as sugarcane and thus increasing the sugar gap by 32%.
3. Salinization of large areas of Egyptian agricultural land due to lack of water allocated to agriculture.
4. Suspending all land reclamation projects and agricultural expansion in Egypt.
5. Increasing the Egyptian food gap to 75% of our total food needs instead of currently 55% [28].
6. Reduction of Nile water quantities flowing into the Mediterranean Sea and consequently the intrusion of the sea saline water to the Delta lands as well as the underground water.
7. Increasing rates of desertification of agricultural land in addition to increasing pollution concentration in the Nile, canals, and banks due to lack of water flows.
8. Possible disappearance of fish from the Nile for 5 years as well as lack of aquatic biodiversity and also in agricultural soils.
9. Adding additional burden on the Egyptian economy for establishing Mediterranean desalination plants for domestic, industrial, and tourist consumption in the coastal cities of El Arish, Port Said, Damietta, Rashid, Alexandria, Matrouh, Salloum, Suez, and Safaga, to save the Nile water for agriculture.
10. Affecting negatively on river navigation and tourism.
11. Declining in national income due to the lack of agricultural production accompanied by the decline in rural development rates and the cessation of antipoverty programs [29, 30].

7.3 GERD and the Threat of Electricity Generation Sector in Egypt

Studies indicate that Egypt’s water deficit accompanied by the construction of GERD will lead to a shortage of hydroelectric power produced from the Aswan High Dam (and all the facilities beyond) with a range of 40% for 6 years as well. Thus, Ethiopia’s electricity generated from GERD would be at the expense of Egypt’s electricity. Moreover, the pumping of water to Egypt would be in the form of a daily quota that depends on Ethiopia’s need for electricity. The river would, then, turn into a canal in which water is rationed by Ethiopian orders.

Consequently, Lake Nasser would have no water importance in addition to the High Dam. It would be even better to demolish it to reduce the evaporation of Lake Nasser [31, 32].

Studies indicate that there will be negative impacts on the High Dam GERD that is completed. Among these impacts are the following [33, 34].

1. Water flows that reach the Aswan High Dam would be reduced during the filling period of GERD, depending on the filling rate and the incoming flood flow rate.
2. Water flows that reach the Aswan High Dam would be reduced by GERD evaporation rate in case it is normally operated (assuming that the main purpose of the dam is to generate electricity).
3. The Aswan High Dam would operate at lower levels, and the value of the reduction would be based on the filling and operating rules of GERD. These rules remain unclear as Ethiopia keeps the right for itself to fill and operate the dam unilaterally. Therefore, the East Nile states should cooperate and coordinate among themselves on filling and operating policies, to take advantage of the electricity generated by the Aswan High Dam [34, 35].
4. The decline in the levels and contents of the Aswan High Dam depends on the flood situation. If the revenue was low, the impact would increase sharply.

8 Conclusions

This chapter presents the basic information on both GERD and AHD and the main impacts as well. Studies confirm that the AHD is so advantageous to Egypt when compared to its adverse impacts, while the GERD negative impacts to Egypt could be disastrous during the years of filling and in case the GERD collapsed. The situation will be more severe if the filling takes place during low inflow period and no sufficient water in Lake Nasser. It is worth noting that the report of the International Panel of Experts (IPoE) pointed out some of the damage that GERD can cause to the downstream state, especially in the light of the lack and severe imbalance in the water, environmental, and engineering studies related to GERD [23]. This, in turn, confirms that GERD does not agree with the principle of "no harm" as one of the governing principles of international rivers [36, 37]. These issues will be discussed in detail in this volume.

Acknowledgment It should be mentioned that Sect. 2 in this chapter was moved from the chapter titled "Importance of Aswan High Dam to Egypt" authored by Nader Noureldin.

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Environmental Impacts of AHD on Egypt Between the Last and the Following 50 Years

El-Sayed Ewis Omran and Abdelazim Negm

Contents

Abstract Egypt will be affected by a countrywide freshwater and energy shortage as early as 2025. The construction of the Aswan High Dam (1964–1971) opened a new chapter in the long and celebrated history of the Nile River with respect to its chemistry, biology, and influence on Egyptian life. Built under a storm cloud of controversy, the Aswan High Dam (AHD) has stood simultaneously as a symbol of the highest in engineering achievement and an example of an environmental threat. The objective of this chapter is to place in perspective important environmental issues related to the AHD. The AHD has now been operational for 50 years. Analysis of the AHD impacts obviously indicates that overall, they have been

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overwhelmingly positive for Egypt. Based on data gathered over the past decades, this chapter reviews the environmental (positive and negative) impacts of the AHD.

AHD would give Egypt protection against drought and flood. For example, droughts happened between 1979 and 1987 and flood between 1998 and 2002 had no influence on water supply downstream from Aswan. Other AHD benefits were (1) production of electricity, (2) providing water for agricultural land reclamation, (3) converting basin irrigation with perennial irrigation, (4) expanding rice production, (5) development of a fishery in the reservoir formed by the AHD, and (6) improvement of river navigation due to steady water level downstream from the AHD.

The Nile is a silt-bearing river, and the Nile Delta and Valley in Egypt are composed of its sediments. The sedimentation rate in the pre-High Dam era was estimated at 0.6–1.5 mm year^{-1} with an average rate of 0.8 mm year^{-1}, used to cover the surface of agricultural soil in Egypt. Since 1964, this annual rate ceased to reach the soil surface, with the following consequences. The AHD has faster the coastline erosion (due to lack of sediment brought by the Nile) in Egypt. Problems created by sedimentation are lake infilling, erosion downstream of dam, deepening of the Nile Delta, and loss of nutrients to farmlands and Delta estuary. The incidence of schistosomiasis or bilharzia increased due to the AHD blocking the natural fluctuations in water height. Important factors contributing to the occurrence of schistosomiasis were poor sanitation and limited awareness of how the disease was transmitted.

The (positive and negative) analysis of selected impacts made in this chapter should provide a clear indication of the difficulties of assessing impacts of any large hydraulic structure.

Keywords Aswan High Dam, Climate change, Egypt, Environmental impacts, GERD, Lake Nasser

1 Introduction

The thinking at the political level in Egypt before Aswan High Dam (AHD) construction was “More water will be required in the coming years as the populations in Egypt keep on increasing.” Due to the utilization of more efficient management practices, some of this extra water will be accessible; however, in most cases, this will not be satisfactory. New dam development will be important to meet this deficit. For a long time, dams have been an essential means for storing water, principally for irrigation. Dams are built for protection against floods, irrigation, hydropower development, water supply, navigation and transportation, fishing, recreation, and water sport. Water and energy are the keys to advancement; this is particularly true in Egypt. Huge dam building is traditionally thought to be a powerful means of river water management, particularly where population is bulging with dramatic increase.

There are different definitions of large dams [1]. A huge dam is a dam with a height of 15 m or more from the ground and has a reservoir volume of more than 3 million m^3. The two main categories of large dams are reservoir-type storage projects and run-of-river dams that often have no storage reservoir and may have limited daily pondage. Reservoir projects store water behind the dam for seasonal, yearly, and, in some cases, multiannual storage and regulation of the river. Run-of-river (weirs and barrages and run-of-river diversion) dams create a hydraulic head in the river to partially divert the flow of the river in the upstream side. With the progress in the technology, dams have been shown to be more critical for power generation. Simultaneously, they have become even larger, partially regulating and utilizing the water resources of large rivers. Building dams for energy production began around 1890; there are greater than 45,000 large dams worldwide, most of which were built after 1950 [1]. Hydropower is still an important renewable and environmentally friendly source of energy, despite its potential negative effects. In addition to that, water resources and their careful utilization and management are of growing significance in the light of increasingly scarce availability and higher demand [2]. Dams will keep on being a critical commitment to the satisfactory management of water resources.

Four storage dams are situated in the Nile Basin: these are the Aswan High Dam (AHD) on the main Nile in Egypt; Roseires on the Blue Nile, Sudan; the Owen Falls Dam on Victoria Nile in Uganda; and newly the Grand Ethiopian Renaissance Dam (GERD), which is under development on the Blue Nile River in Ethiopia. Overall, the AHD project was a great construction accomplishment, and the points of interest exceeded the impediments [3]. More than 30,000 Egyptian personnel completed the dam development, which was supported by a few hundred specialists from the Soviet Union. The main role of the Soviet was to provide technical assistance and supervision of the project. Not always is a dam the right or best solution in a given situation (e.g., [4]). The AHD was a critical and urgent solution to some accumulating problems in Egypt, which, if delayed, would have catastrophic impacts [5] for the coming reasons. First, the 1952 revolution regime introduced a huge economic reform to transform the country from an agricultural to an industrial society, which requires sources of energy. The best option at that time for Egypt was hydropower. Reform would not be conceivable without the cheap power that the AHD provided. If the project was postponed, the reform would be delayed. The second reason was that before the dam, Egypt was reliant on the Nile River for drinking and agricultural water. When the river's flow decreases, the country suffers from drought. In addition, when the flow exceeds the limit, the country suffers from flooding. In both cases of drought and flooding, there were deaths and economic losses. The answer for this issue was to regulate the river's flow through the AHD. Any postponement in building this dam would mean extended vulnerability to the threat of flood and drought. The significance of these two issues was getting worse each year because of the rapid population growth [5]. Throughout the 1960s, the population increased by more than 2.5% annually. On average, the rate of increase was 0.75 million people per year [6]. Consequently, the demand for food, water, electricity, jobs, and other services had increased. This rate of population growth would be unattainable without developing new agricultural lands, producing more energy, and modernizing the economy to make occupations. The solution at that time was the construction of the AHD.

However, most large dams built throughout the world have stressed the economic and social benefits to society and largely ignore any long-term environmental impacts [7]. A substantial resettlement was carried out for the Nubian people. Therefore, the main objective of this chapter is to assess the environmental impacts of AHD on Egypt. Our core questions, which must be answered, are as follows:

1. Do the AHD was a positive project through troublesome time in Egypt, and why?
2. Can we elaborate on the negative impact that threatened AHD project and how they threatened the project?
3. What helped that project to achieve success despite these difficulties?
4. How the lessons gained from AHD project achievement can be implemented to achieve the environmental and ecosystem sustainability?

2 Dam Description and Difficulties Associated with the AHD Execution

AHD is a rock-fill dam, which was provided with a grout curtain (213 m deep and 111 m high) as shown in Fig. 1. The dam is fitted out with a diversion canal on the eastern bank of the river designed to pass a discharge up to 11,000 m^3/s. It comprises of open canal reaches in the upstream and downstream parts joined in the middle by the key control tunnels under the dam body. The reservoir at its storage level (183 m amsl) is situated between latitudes 23°58′N in Egypt and 20°27′N at the Dal Cataract in the Sudan and between longitudes 30°07′E and 33°17′E. The reservoir is about 496 km long and incorporates two sections: Lake Nasser in Egypt and Lake Nubia in Sudan.

Some researchers are claiming that Egypt would not be able to fill the AHD reservoir, which is one of the criticisms related to AHD development. Scientists in this time did not recommend storing a large amount of water at the south of Egypt, fearing a high evaporation rate. The reason was because of the high seepage values and high evaporation (3.8 mm day^{-1} in January–10.8 mm day^{-1} in June), which was calculated as 10.0 BCM per year in the treaty between Egypt and Sudan [8]. However, the reality after operation did not support such criticisms. The investigators concluded that there was no appropriate place to store water north of El-Khartoum, except in the location of the Aswan reservoir; therefore, they recommended increasing the reservoir capacity for the second time [9]. Other authors [10] reported that "Egypt should concentrate on projects on its own land. The 1952 revolution leaders understood such geopolitical situations and began to look for another alternative that could ensure Egyptian water requirements, and therefore they decided the AHD construction with big interest" [10].

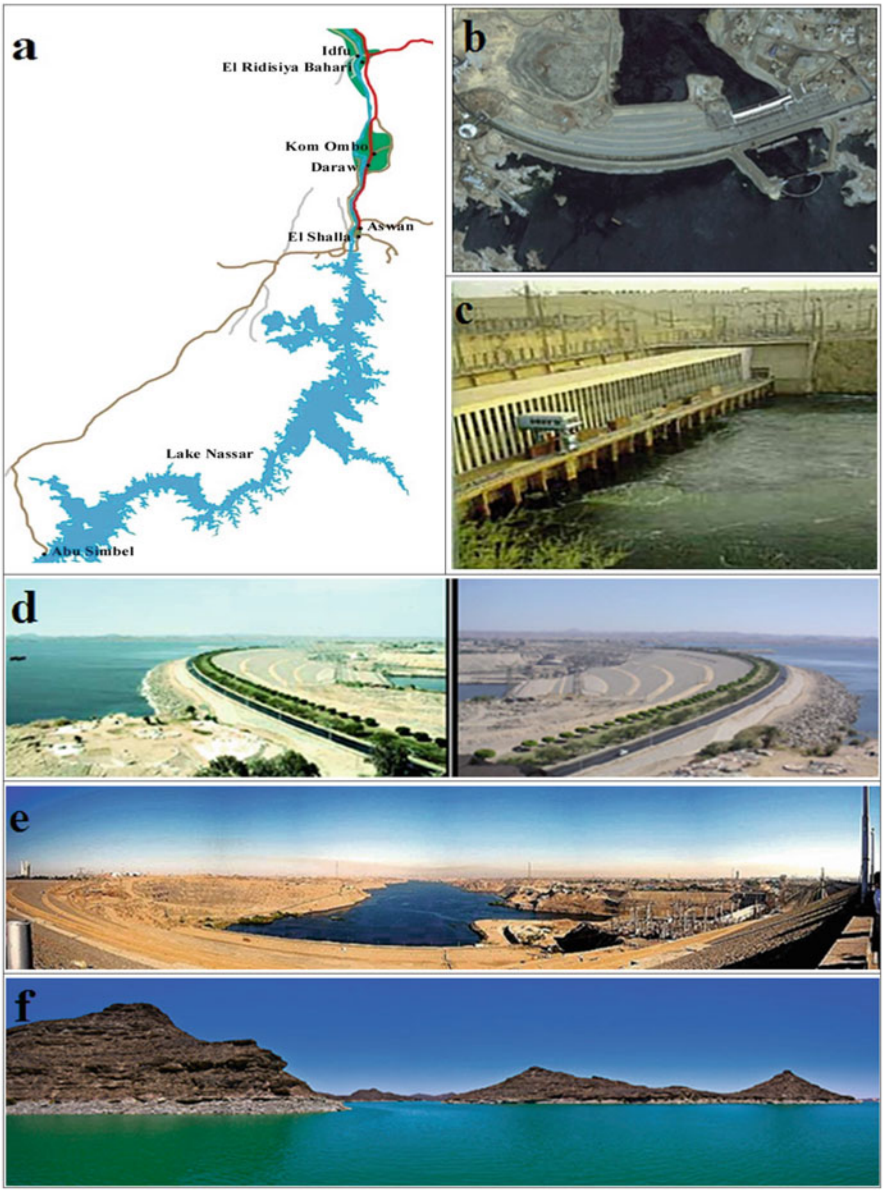

Fig. 1 (**a**) Map shows Lake Nasser and Aswan High Dam. (**b**) Aswan High Dam. (**c**) Sample hydroelectric generators located at Aswan High Dam. (**d**, **e**) A panoramic view holding back Lake Nasser and (**f**) Lake Nasser, Egypt

Funding challenges were associated with the AHD execution, which were transformed into political conflicts. The existence of a huge lake upstream of the dam is another challenge. Some ancient monuments and some tribes occupied settlements at lake location on both sides of the Egypt and Sudan border [11]. In Egypt, the evacuated (Nubians) tribes who were living on the Nile shores for a length of 320 km south of Aswan had moved to Kom Ombo, north of AHD. There was another Sudanese tribe in Wadi Halfa, and Egypt paid an indemnity to Sudan to evacuate them.

A unique microclimate (reservoir ecosystem), created by the reservoir, prevails in this region. The microclimate is characterized by a higher incidence of cloud cover directly over the water, lower air temperature, higher wind velocities, and an increase in relative humidity of the region. These meteorological anomalies are very localized and do not influence the environment surrounding the reservoir. The breakdown of stratification begins with the incoming floods in the southern region and the gradual cooling of the climate in the northern region. The northern two-thirds of the reservoir is lacustrine in nature, while the southern third varies from riverine to semi-riverine and lacustrine conditions depending on the magnitude of the annual flood. The satellite images clearly showed that algae, aquatic macrophytes, and aquatic hydrophytes concentrate along the near-shore zone of the reservoir. The images indicate that while the main channel of the reservoir remains relatively clear of vegetation, phytoplankton is distributed throughout the central area of the reservoir. High densities of vascular aquatic vegetation are found within the embayments (called khors).

3 Environmental Impacts of AHD on Egypt

There are places in the world where dam building is not so problematic. Iceland, for instance, has nearly limitless hydroelectric power and is working to dam many of the rivers in the country's interior. For this situation, there are no people to resettle, and no international boundaries involved. The only "loss" is that of spectacular canyons and valleys.

3.1 Identification of Positive vs. Negative Impacts

It is critical to characterize the effects into categories, because whether mitigation measures are required will rely upon the apparent significance and "direction" of the impacts. The measures should lead to improving positive and reducing negative effects, where required. This requires a consensus on what is positive, what is negative, and how much cost is allowed.

For mitigation, the correct "relevant environment" identification is fundamental. Some impacts are easy to identify, to understand, and to assess in their magnitude, whereas others are not. The following pairs of expressions are normally used to characterize impacts [1]:

1. Clearly identifiable category. This category might be rather clearly identifiable and therefore undisputed in most cases.
    (a) Direct-indirect impact is caused immediately by the project itself, whereas an indirect impact is a consequence of a change caused by the project.
    (b) Total-partial impact is used to characterize the magnitude of the impact, considering a specific item.
    (c) Permanent-transient impact characterizes the duration of an impact.
2. Not clearly identifiable category.
    (a) Important-negligible. This is an attempt to characterize the meaning of an impact; terms that are synonyms are "relevant" and "irrelevant."
    (b) Positive-negative. Sometimes it is also termed "desirable" and "undesirable." These expressions are used mostly to characterize impacts on human activities or (potential or actual) human uses or perceptions of impacts and their consequences.
    (c) Acceptable or not acceptable. All this finally ends in a dichotomy on the acceptability of an impact. "Acceptable" usually means "according to legal standards," but in the absence of such standards, it can also mean that a consensus (among whomever) has been reached. The consequence of an unacceptable impact would be that the project in question cannot be implemented.

Any large infrastructure like the AHD invariably has various impacts, some of which are positive while others are adverse, and some are very significant while others are minor. It is simply not possible that for any major project, there will be only benefits and no costs and only beneficiaries with no one having to bear costs. Normally, there is a combination of costs and benefits, and there will always be beneficiaries and people who will have to pay the costs. The AHD has had a tremendous impact on the Egyptian way of life, agriculture, and the environment.

The AHD and its reservoir have resulted in a number of what can be called side effects, some of which are positive and the rest are detrimental, to both nature and society. Brief overviews of the major effects, positive and negative, of the AHD are presented next. Important environmental influences of dam construction on nature and on society can be classified as follows:

1. Influences on nature: (a) the *area around dam and reservoir* (microclimate change, induced earthquake, water leakage, land sliding), (b) *interior of reservoir* (water temperature change, eutrophication, turbidity, sedimentation), (c) *downstream of the dam* (riverbed change, salt accumulation in River Delta soils, seawater intrusion, bank erosion, deterioration of soil fertility, coastal erosion), and (d) *others* (impact on fish, impact on wildlife).
2. Influences on society: (a) *area in around reservoir* (problems during construction, landscape preservation and recreation, displacement of population, protection of archeological relics) and (b) *whole river basin* (water-borne and water-related diseases).

It ought to be well understood that not all of the above-listed items have adverse impacts on the nature and/or society. Sediment trapping and inundation of archeological and monumental relics are two examples of the negative impacts of dam construction, whereas hydroelectric power generation and flood protection are examples of positive impacts.

3.2 Positive Impacts

The usefulness of dams has always been obvious, be it the energy generated, the increase in water available for irrigation and drinking water supply, or benefits of flood regulation and protection, navigation, tourism, and so on. Protection against floods, larger irrigated surface, and increased water supplies for domestic and industrial purposes and production of clean energy provided by the greater shares in the Nile water made available to Egypt and the Sudan are positive impacts. Lake Nasser turned into an important fishing site, supplying food and livelihood for the population around it.

3.2.1 Stability of Water Resources

The major advantage of AHD was creating a multiyear reservoir to enable water resources stability through these multiyears. Throughout the drought period in Egypt (from 1981 to 1988 and from 2006 to 2017), the AHD role in saving Egypt was evident. In addition, the dam increased Egypt's water quota from the Nile by 7.5 BCM by stopping freshwater release to the sea [12]. The dam has supported a high population growth rate in Egypt, because it encouraged an expansion to agriculture, energy production, and manufacturing. One of the positive effects was that it enabled agriculture to move from basin irrigation to year-round irrigation, so crops could now be produced also during the dry months. Since the fear of flooding no longer existed, farmers were able to work in the fields year-round. The AHD created a 30% increase in cultivable land in Egypt and raised the water table in the Sahara.

This water stability is the major reason for transformation of basin irrigation to perennial irrigation. Approximately 0.42 million ha, mostly in Upper Egypt, used to be irrigated by the floodwater (basin) irrigation method. Only one crop per year could be produced with this method. These lands were changed totally to perennial irrigation, whereby water is available at any time during the year. As a result, two or more crops can be produced annually. This means that the crop area was doubled or tripled in these regions. The people living on these lands were completely settled, leading to a better life with higher yields and production.

3.2.2 Land Reclamation

The water secured by the AHD storage was the central factor that permitted the government of Egypt to accomplish its horizontal land expansion program. The AHD benefits Egypt to support its plans for land reclamation and greening the desert. About 0.84 million ha were reclaimed, irrigated, and cultivated using the water made available by AHD reservoir. This region involved lands in the East, West, and Middle Delta and along the Nile Valley close to the old land. Irrigation dominates agriculture in climatically dry Egypt and northern Sudan. Egypt has begun Northern Sinai irrigation project that comprises El-Salam Canal under the Suez Canal and eventually will use additional 4.4 billion m^3 of water. When completed in 2017, the New Valley Project will divert another 5 billion m^3 of water annually. About half a million families will be settled on these new lands. This will make chances for new employment and additional production, especially of foodstuffs that Egypt needs to handle its increasing population and to minimize food imports.

3.2.3 Increase the Yield of the Agricultural Lands

Agriculture in the Delta has usually benefited from the water and silt deposited by the flood (the silt comes from eroding basalt lava in the highlands of the Nile main source). This silt made the Nile Delta one of the richest agricultural areas in the world and one of the most ancient human civilizations.

By controlling the Nile River flow, the AHD has secured a steady and continuous flow of water particularly during summer when the natural flow of the Nile is much lower than irrigation requirements. This availability of water is essential for flexibility of agricultural planning, crop patterns, and crop rotation. In addition, farmers were guaranteed that their water needs would be met. They could irrigate crops occasionally in accordance with the schedule of planting and growth until harvest. This produced a very high crop yield in spite of the poor yield of the catchment during those years. As a result, the area of agricultural production rose to about 6.38 million ha, compared to about 3.91 million ha in 1952. Yield production per hectare has increased enormously since construction of the AHD. In addition, the water abundant, which stored in the front of AHD Lake, helps to increase the strategic (high water consumptive) crops. These crops include rice, sugar cane, sugar beet, clover, and banana.

3.2.4 Reduced Climate Change

Susceptibility against climate change was not present when the AHD building. Climate change, extreme weather events, sea level rise, growing water demand from other sectors, groundwater depletion, and pollution will affect agriculture production in different regions of the world. The AHD electric power station is still the largest hydropower station in Africa, with a total capacity of 2,100 MW. It produces around 10,000 GWH. From its construction until July 2014, the AHD has generated more than 353,779 million kWH. This hydropower saved 74 million tons of diesel, thus reducing the emissions of carbon dioxide by 230.0 million tons [12]. AHD also benefited the industry by providing cheap electric power supplied even the most remote Nilotic villages with electricity.

3.2.5 Improved Navigation and Tourism

The frequent changes in water levels before AHD negatively affected inland navigation. During the flood season, there was insufficient space under the fixed bridges to passing ships. In other periods, the canals might not have enough water depth for navigation. The stability of water levels in the Nile and the main canals after the AHD construction has helped improve navigation up and down the Nile all the year. This helps Egypt to establish the Nile cruise hotel navigation and several of navigation restaurants across the Nile, which increase the upcoming tourist. The annual number of tourists to Aswan has risen from 80,000 in 1960 to about 300,000 in year 1997 [13] and to one million in year 2010.

3.2.6 Protection Against Floods

Before the AHD construction, Egypt loses 22–34 BCM per year of Nile water throughout the flood period in the Mediterranean. With the reservoir storage provided by AHD, the floods could be lessened, and the water could be stored for later use. Reservoir storage contents can be converted into water levels. Figure 2 shows the reservoir levels in the period 1968–1990 and from 1966 to 2001. From this figure, it can be seen that the reservoir remained at high levels during the period 1976–1982. Higher levels were even reached around the end of the 1990s. The drawback of this situation is the risk of failure in storing future floodwater should high inflows persist. Increased reservoir storage losses are certain to occur. The advantage is the development of hydropower at full capacity of the turbines. On the contrary, the reservoir level reached its low levels between 1986 and 1988. The advantage of that situation is the reduction of the risk of flood and storage losses, whereas the interests of power production and land irrigation could have been adversely affected.

3.2.7 AHD Generate Our Electricity

One of the main objectives of constructed the AHD is to generate cheap hydropower. Egypt searches for an inexpensive and sustainable source of generating electricity that is always found in hydropower generation. Power generation began in 1967. The dam powers 12 generators each capable of producing 175 MW, with a total of

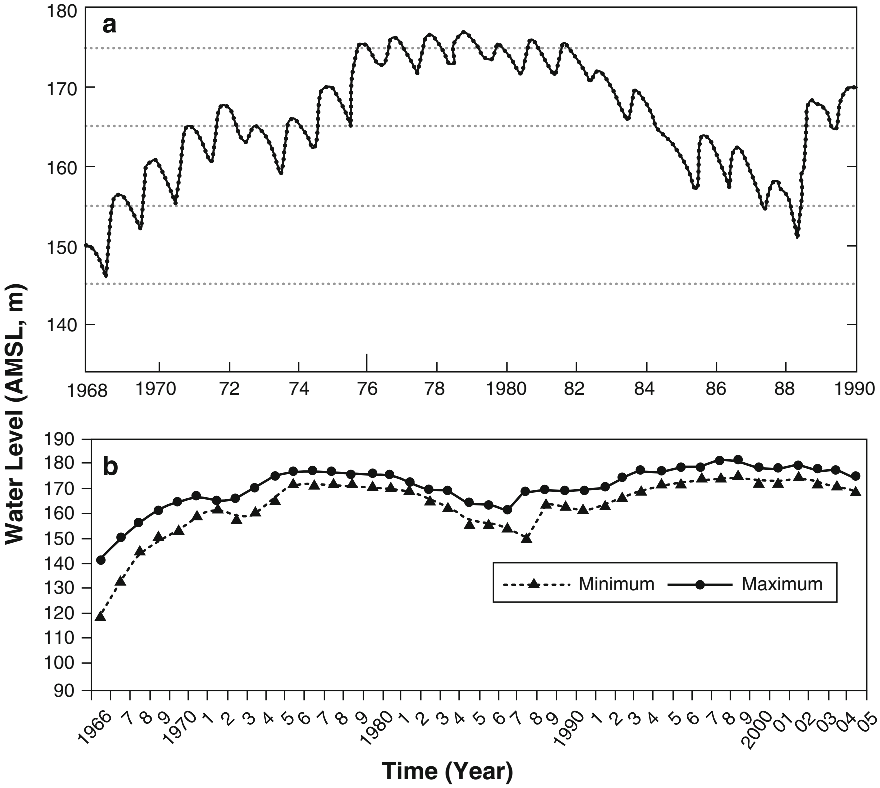

Fig. 2 Water level of the reservoir of the Aswan High Dam, 1968–1990, (**a**) and the yearly amplitude of water level fluctuation in the period from 1966 to 2005 (**b**) [14]

2.1 GW, which increases the percent of access electricity in Egypt especially in rural area and village, in addition to complete covering all cities [13].

3.3 Negative Impacts

In the 1970s, the Aswan High Dam turned into a global symbol of environmental and social problems caused by large-scale development projects. Impacts of AHD touch upon a wide range of life aspects, containing "a change in water quality, as the maximum water release through the AHD is about a quarter of the former flood" [14] and is practically silt-free. Construction of the AHD in the 1960s has served to lessen the quality and quantity of soil nutrients reaching the Nile Delta. Bed and bank erosion occurred in the downstream reaches of the Nile, produced by a change in river water levels and flow velocities, and the promontories of the Delta started to erode instead of progressing into the sea [14]. Following achievement of the dam, there have been widespread problems, ironically caused in part because the annual flood no longer occurs. Different negative issues will be discussed.

3.3.1 Increased in Soil Salinity and Water Logging of Agricultural Land

In Egypt's Nile Valley, the water table has been rising substantially nearer to the surface in many places. One particular danger is the salt formation. The sand and soil of the Nile basin are naturally salty. The annual Nile flooding would wash the salt into the Mediterranean before AHD was built. Before the AHD construction, groundwater levels in the Nile Valley fluctuated 8–9 m year^{-1} with the water level of the Nile. During summer, the groundwater level was too deep when evaporation was highest to allow salts dissolved in the water to be pulled to the surface through capillary action.

As AHD brought a halt to the flooding, and salts were added in the form of mineral fertilizers, the natural salt began to develop. Over-irrigation, inefficient water utilization, insufficient land leveling, and the intensification of cropping patterns have also contributed to an increase in the groundwater level of irrigated areas. With heavy year-round irrigation, groundwater levels stayed high with little fluctuation leading to water logging. Soil salinity also increased because the distance between the surface and the groundwater table was small enough (1–2 m depending on soil conditions and temperature) to allow water to be pulled up by evaporation. So, the relatively small concentrations of salt in the groundwater are accumulated on the soil surface over the years. When water evaporates in these hot areas, it brings salts to the soil surface. This is called salinization. If too much salt rises to the surface, it can kill the plants and reduce yields.

Swamps were created due to irrigation and more intensive farming, joined with inadequate drainage. The water table rise has led to accumulation of harmful salts, fertilizers, and pesticides in the upper layers of the soil. The Nile water no longer deposits its sediment on the farmland; consequently, the farmers have to use artificial fertilizer as a substitute for the nutrients. The water table had increased meanwhile the dam was built, increasing the hazard of fertilizer and other agricultural waste products that may seep into the Nile River when its water level is low. Since all soil is permeable, water will always leak out of the AHD Lake. The high water level in the AHD Lake forces the water into the surrounding soils. On the other hand, water can flow back into the lake when its water level is low. The intensification of irrigation throughout the year, with the excessive use of water, has led to an increase water table level in agricultural lands. This demands announcing big projects to install subsurface drainage systems throughout the agricultural area [12]. Since some of the farmland did not have proper subsurface drainage to lower the groundwater table, salinization gradually affected crop yields. Over half of Egypt's irrigated lands are currently evaluated medium to poor in quality due to poor drainage, which has led to soil saturation and increased salinity. The high cost of creating drainage systems is the principal issue. Absent and/or ineffective drainage systems contributed to the development of salinity and water logging, which reduced land productivity. A total of about 2.1 million ha required subsurface drainage at a cost that exceeded the construction cost of the AHD. Only 20 years after completion of the AHD, the problem was seriously addressed, and a large-scale drainage program was initiated.

3.3.2 Development of Land Drainage

Historical development of land drainage increased suddenly after the AHD construction (1964–1970), together with the introduction of perennial irrigation, high cropping intensities, and the high increase of water use per unit area. Consequently, the natural drainage system could no longer survive with the increased percolation losses from irrigation, and lot of land became waterlogged and/or salt-affected.

The first Nile Delta drainage project, including 400,000 ha, was financed by the World Bank [15] during the period 1971–1980. At that time, it was the world's largest drainage scheme. Drainage projects covering an area of 1.3 million ha were completed by 1987 in the Delta and Upper Egypt, with subsurface drainage systems and improved open drainage channels. The subsurface drainage system in Egypt involves buried pipes that form a regular pattern of field and collecting drains. The field drainage system is comprised of subsurface field (lateral) and collector pipes run by gravity. The piped collectors discharge into open main drains, and the water is then pumped into large open gravity drains, which eventually discharge into the Nile River or the sea. Pumping is essential everywhere in the Delta and the Valley, except in a few areas in Upper Egypt, where there is sufficient gradient to dispose of the effluent freely by gravity [16]. In the late 1970s, the Egyptian Public Authority for Drainage Projects (EPADP) launched a comprehensive drainage construction/rehabilitation program that covers 3.36 million ha of agriculture lands. It has either constructed new surface (open) drains or rehabilitated (remodeled, deepened, widened, and removed weeds from) existing open drains. By the end of 2004, the EPADP had achieved 3.02 million ha of surface open drainage. Concurrently, they announced a long-term plan for flexible creation of subsurface drainage in another 2.69 million ha area. This largely allowed the use of mechanized pipe-laying, plastic pipes, and synthetic envelope materials for public and private contractors [17].

3.3.3 Human Issues and Resettlement of the Nubians

To build the dam, both people and artifacts had to be relocated. Although the Nubians lived in two different states, but demographically, they are considered as one community. Their unique cultural heritage distinguished them from both the Egyptians and the Sudanese. At the time of the AHD construction, northern parts of Nubia had already suffered from the inundation of their land. In 1963, the entire Nubian population (Egyptian and Sudanese) was subjected to resettlement. Over 90,000 (by some estimates over 120,000) Nubians had to be moved. Those who had been living in Egypt were moved about 45 km away (plain of Kom Ombo), but the

Sudanese Nubians were relocated 600 km from their homes (Khashm El-Girba, in the east of Sudan). The resettlement program was carried out very quickly, with severe consequences for the ~50,000 farmers who had to abandon their land. Their new settlement, called New Nubia, was far from arable land. Agriculture in Nubia had conventionally been based on the annual flood of the rivers. The regulation of the rivers put an end to this kind of farming. In addition, arable land was submerged by the reservoir. The people tried to farm the riverbank instead, causing increased erosion. Efforts to start a system of crop rotations clashed with tradition and did not work out.

The area that they were moved could not sustain the population, resulting in poverty and rising death. Many people were exposed to sleeping sickness due to the resettlement areas that were infested with the tsetse fly. Because of poor planning, about 50,000 people ended up in camps similar to refugee camps. The hygiene in these camps was very bad, and epidemics flourished. The resettlement program made the Nubians dependent on food aid in order not to starve. The parasitic disease schistosomiasis has been associated with the stagnant water of the fields and the reservoir. Since the opening of the AHD, the number of individuals affected has increased. Construction of the AHD initiated an amplified rate of schistosomiasis among the population – from 21% to almost 100%. Similarly, the first cases of malaria in northern Africa happened after the establishment of Lake Nasser. Mosquitoes want shallow stagnant water to breed, and the lakeshore is the perfect environment. The recent identification of West Nile virus also indicates a water-bred and mosquito-borne disease that would not flourish if Lake Nasser had not been built. Nubia is also of wonderful historic importance, as this area – located between the first and third cataracts – was the Kingdom of Kush, created during the Middle Kingdom about 2000 years BC (4000 years BP). The government became aware that many artifacts and antiquities would be submerged.

Ancient (Philae and Abu Simbel) monuments (Fig. 3) had to be transferred to higher locations. The temple was submerged for most of the year after the construction of the Aswan reservoir. The two temples were the most famous temples, and a major effort was undertaken to save them during the period between 1964 and 1968. The work started by building a dam around the temples to save them from the water that was gradually rising in the lake. Then, the temples were cut into large sections and moved to another place where they were reassembled again. The new place was 210 m from the original location, about 65 m above it.

3.3.4 Changes to the Egyptian Fishing Industry

Five years after the dam was built, 2,000 fishermen managed to catch 3,628 tons annually, while the catch was likely to be around 20,000 tons. Ten years later, the catch had dropped to 907 tons.

The dam dramatically affected the Mediterranean fishing industry. The river that holds vital minerals and nutrients for fisheries in the sea at the river mouth normally carries the silt and sediments. Unlike more fertile, nutrient-rich seas, such as the

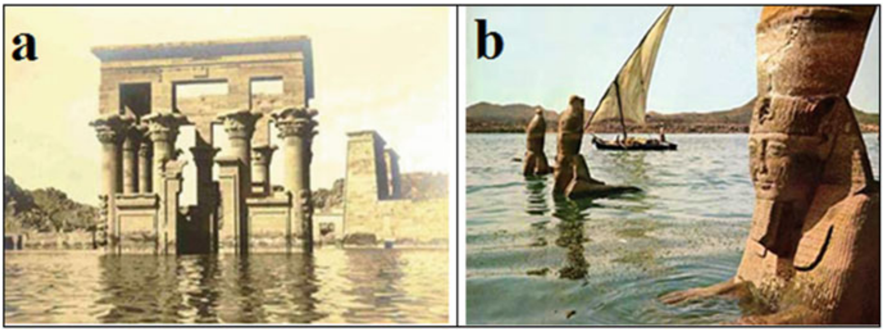

Fig. 3 (**a**) The Great Temple of Ramses II at Abu Simbel. The Kiosk of Trajan is in the foreground, while the Temple of Isis is at the right rear. The reservoir of the first Aswan Dam flooded the complex for much of each year. (*From* the Collections of the Kelsey Museum). (**b**) Twin temples of Pharaoh Ramses II relocated by UNESCO

North Sea and the Arabian Sea, the Mediterranean is noted for its nutrient-poor waters that contribute to a low level of primary productivity (creation of organic matter through photosynthesis by phytoplankton). In the Mediterranean Sea, primary productivity is unusually low for several reasons. The circulation of the sea brings low-nutrient water from the North Atlantic through the Strait of Gibraltar and allows nutrient-rich bottom water to exit the sea through the same opening. The arid climate of the region and the low levels of nutrient-rich river runoff also contribute to the low productivity of the Mediterranean.

Fifty percent of the Nile flow drained into the Mediterranean prior to the High Dam was built. During an average flood, the total discharge of nutrient salts was estimated to be approximately 5,500 tons of phosphate and 280,000 tons of silicate. The nutrient-rich floodwater, or Nile Stream, was ~15 km wide; it extended along the Egyptian coast.

A negative impact of the AHD was the loss of the Mediterranean sardine fishery. The fertility decrease in the southeastern Mediterranean waters triggered by the AHD has had a catastrophic effect on marine fisheries. The fishery was situated at the mouths of the two main Nile tributaries to the sea, the Rosetta and the Damietta. Suspended silt carried by the river fed the fishery with nutrients, which sustained a large biota population. Closure of the river at Aswan trapped the silt, which then started to form a delta within the reservoir. The Delta ecosystem reacted immediately to the loss of nutrients, and the sardines could no longer be supported. The average fish catch declined from nearly 35,000 tons in 1962 and 1963 to less than one-fourth of this catch in 1969. The hardest hit was the sardine fishery from a total of 18,000 tons in 1962 to a mere 460 and 600 tons of sardines in 1968 and 1969. The shrimp fishery also took a heavy toll as the catch decreased from 8,300 tons in 1963 to 1,128 tons in 1969. In 1978, the fisheries were so poor that only a small part of the population was able to live off fishing.

Since the late 1980s, the total fish catch (pelagic and bottom) off the Egyptian coast has developed to levels similar to those that occurred before AHD development. Whether this is due to improved fishing efforts or recovery of fish stocks is not clear. In 1992, there has been a clear growth in the sardine catch along the Egyptian coast (8,590 tons) with most of the landings coinciding with the period of maximum discharge from the coastal lakes during winter. Advocates of the AHD project resolved this loss with the argument that a new freshwater fishery could be developed in the Aswan reservoir. Fish could be taken from the reservoir with significantly less effort than from the sea fishery.

3.3.5 Erosion of the Delta

The high amount of silt in its water was one of the fundamental attributes of the Nile water. Nile use to carry around 134.0 million tons of silt, out of which 125.0 million tons came during the flood months. Most of this amount was conveyed to the sea, but around 12% use to settle on cultivated lands. Most of these suspended solids settle in the lake since the AHD construction, and only 3% of them travel downstream from the dam [18].

Heavy erosion in the Nile Delta was caused due to the reduced supply of silt and sediment from the annual flood. The erosion, combined with normal compaction of Deltaic sediments, has decreased the inhabitable land on the Delta for the first time in over 10,000 years. Different set of problems have been made because of the absence of silt reaching the Delta farther upriver as well. Silt now is trapped behind the AHD, where it settles out of the water and falls in thick layers on the floor of Lake Nasser. As a result, the reservoir becomes smaller each year and is less able to handle the water and electricity generation needs of the nation.

The primary drastic effect is the entrapping of the full silt load of the Nile water in the reservoir and its following effect on the downstream. Sediment investigations in the post-dam era have shown that the mean annual suspended load is between 125 and 135×10^6 tons year^{-1} corresponding to a volume of about $92 \times 10^6\ \text{m}^3\ \text{year}^{-1}$ [19]. This annual rate combined with a trap efficiency of 98% brings the life age of the reservoir to 350 year, instead of the design figure of 500 year. An amount of $2{,}800 \times 10^6$ tons of sediments has been deposited in the reservoir from 1964 to 1989. This amount has led the original river bed to rise in the course of years to what is shown in Fig. 4. This figure shows that the accumulation of sediments up to the year 1990 has been confined to the upper 270 km of the reservoir.

The reservoir has a trapping efficiency of 99%, which means that only clay-sized particles in suspension are discharged through the dam. All sand and silt-sized particles stay in the reservoir. However, as the reservoir was filling between 1971 and 1978, sediment-laden water traversed the entire length of the reservoir. As the reservoir filled, the velocity of the flow declined, and so sediment was deposited progressively upstream from the AHD.

The AHD Authority has conducted annual surveys of sediment deposition in Lake Nasser/Nubia since 1964. The surveys conduct a cross section using echo sounding at 45 points along the length of the reservoir from the AHD to 500 km upstream at Dhaka. The cross sections demonstrate that almost all sediment buildup

Fig. 4 A seawall protection to stop the Nile Delta being eroded by the sea

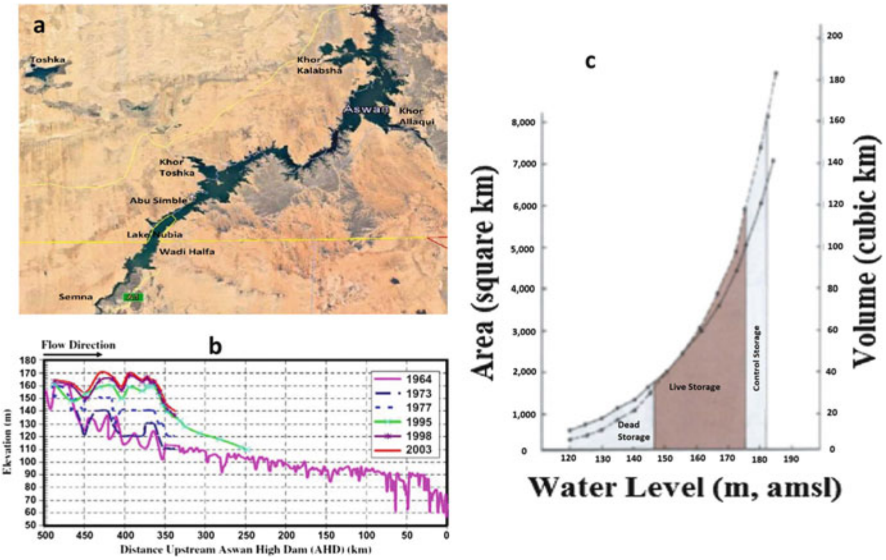

Fig. 5 (**a**) Active sediment deposition zone. (**b**) Longitudinal section of the lowest bed elevation of Lake Nasser/Nubia between 1964 and 2003 [20]. (**c**) Reservoir surfaces area and volume at different levels

is confined to between 350 and 500 km upstream of the AHD as shown in Fig. 5. Sediment depth ranges from virtually nothing near the AHD to over 75 m at the second cataract of the Nile in North Sudan.

Approximately 26% of the reservoir capacity is dead storage (Fig. 5). From the outset it was known that the Nile annually carried approximately 60–180 million tons of silt, depending upon its flow. If a dam was constructed, this sediment would be deposited in those parts of the reservoir where stream velocity slowed. As the reservoir filed, the points of deposition gradually worked their way upstream from the dam, and a delta started building down into the reservoir. Deposition volume added in any 1 year depended basically upon the silt production from the Blue Nile (the headstream of the Nile) as it flows through lower sections of the Sudan. Mean yearly storage of silt in the reservoir has been estimated to be 110 million tons. At present rates, silting would take approximately 500 years to occupy the equivalent of the dead storage in the reservoir, but silt already is encroaching upon live storage in the upper reaches.

3.3.6 Riverbed Degradation and Coastal Erosion

Because of the reduction of suspended material and increased velocity of water released from the High Dam, riverbed degradation and coastal erosion are problems downstream from Aswan.

Although coastal erosion is a process that has been going on along the Egyptian Mediterranean Sea since ancient times, there is no question that AHD execution exacerbated the process and is a serious problem and efforts to slow erosion has been largely unsuccessful. Four simultaneous processes are discussed: (1) the AHD traps all of the sediment, which used to feed the shoreline; (2) the sea level is rising; (3) the Delta is subsiding; and (4) dozens of drainage canals that connect to the sea send tons of sediment into the Mediterranean Sea annually. The sediment derives from fields throughout the Delta.

The coastline retreated principally at near mouths of Nile branches, the Rosetta and the Damietta as shown in Fig. 6. The annual rate of coastal erosion between the years 1990 and 2002 averaged 30 m along the Damietta peninsula. It decreased to about 20 m year^{-1} between 2002 and 2014. The decrease may be because of coastal protection projects established in the area including the installation of sea walls, rip-rap, and levees, but the protection devices have been unsuccessful elsewhere.

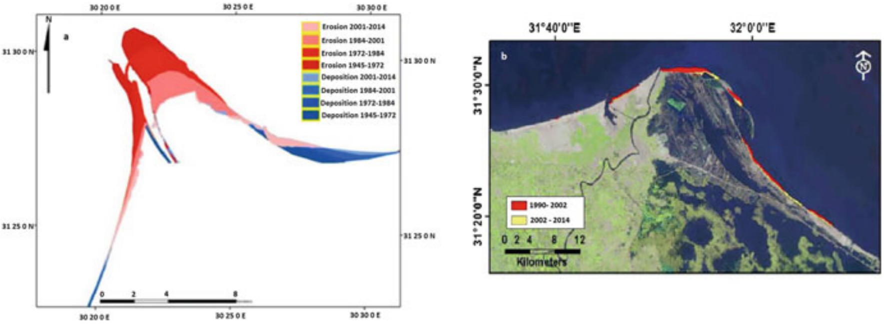

Fig. 6 Coastline changes along Rosetta between 1945 and 2014 (a) and Damietta (b) outlets between 1990 and 2014 [21]

Coastal erosion along the Mediterranean, on the other hand, is a very serious matter, which merits attention and remedial action. The Northern Delta has lost land to the Mediterranean since recorded time. The sea's level has risen about 2 m since Roman times, and the Delta itself seems to be subsiding at approximately the same rate. At the Nile Delta's coast, "a minimal relative sea-level rise of ~100 cm is predicted between now and the year 2100." If the prediction is accurate, the new sea level will be around 1 m higher than the average sea level along Egypt's Mediterranean coast. This, in addition to land subsidence and salinization of agricultural lands in the Nile Delta, will likely have a significant impact on Egypt's population, agricultural production, and the overall habitability. "It is not necessarily that all towns and cities along Egypt's Mediterranean coast will be submerged, but seeping seawater and the increasing salinity of soils may make the area uninhabitable". A 1-m sea level increase could result in the loss of about a third of the Nile Delta's arable land and could displace over two million people. Soil in the Delta region is being submerged at a rate of 1 cm each year due to rising sea levels, coupled with land subsidence and sediment compaction, and that the intrusion of seawater is already resulting in highly saline soils along the northern portion of the Nile Delta.

The Nile has two outlets to the Mediterranean, the Rosetta to the west and Damietta to the east. Both peninsulas of the tributaries have retreated by several 100 m and could breach into either the brackish water lakes fringing the coast or agricultural fields. During heavy storm events during the winter months, seawater does invade the coast lands causing a number of environmental problems. The primary concern over seawater intrusion is for the protection of groundwater quality. Another potential environmental impact that would result from seawater intrusion is the loss of the fishery practiced in the brackish water lakes that fringe the coast of Egypt. Approximately 90% of the fish consumed in Egypt are taken from these lakes, and most of the species would not tolerate significantly higher concentrations of salt. During the flood period, the freshwater that goes to the sea encourages salmon fish to come to the northern shores, which was a big benefit for the fishers. This has stopped after the AHD construction.

3.3.7 Water Quality Changes

The Nile has historically been considered a relatively "clean" river due to the absence of any major industrial activity along its banks. Sources of pollution consist primarily of domestic sewage from local villages. The self-cleansing ability of the Nile is thought to be sufficient for even today's large population within the valley. Two changes in the river's use resulting directly from the Aswan High Dam are responsible for a deterioration of water quality within the river. The amount of agricultural drainage water returned to the river increased considerably as basin irrigation was phased out. Additionally, farmers began to apply chemical fertilizers to replace the nutrients formally brought in each year by the silt. This highly nutritive water has resulted in serious seasonal blooms of algae, phytoplankton, and hydrophytes throughout the irrigation and drainage network, as well as on the main Nile.

The density of phytoplankton has increased more than tenfold since pre-dam conditions.

3.3.8 Decreasing the Fertility of the Agricultural Lands

Unfortunately, this dam has caused a big change in the lives of farmers downstream from the dam. Usually when the river flooded once a year before the dam was built, it deposited fertile soil from upstream on its banks downstream. This washed-up soil (clay and silt) was extremely fertile and renewed itself every year during the flood season. These fine particles release some important essential nutrients for the plant growth and soil fertility. When it is exposed to weathering, it produces secondary minerals (e.g., "mica" as primary mineral to "smectite" and "vermiculite" as secondary clay mineral) plus potassium, calcium, magnesium, iron, phosphorus, zinc, and many plenty of nutrient minerals that fertile the soil. Since the dam was built, the annual flood has stopped. The river used to deposit 120 million tons of silt onto the Delta each year. Now only 50 million tons is deposited because the rest is trapped at the Aswan Dam. The dam increases the use of chemical fertilizers because it blocked the sediments that came with the floodwaters and prevented agricultural land from its benefits. All the farmers downstream have to use fertilizers to grow their crops, which makes it more expensive. Many fertilizers consist of dangerous chemicals that can leak into the ground and drinking water systems if not used properly. Urea fertilizers, for example, produce "ammonium carbamate," which has toxic effects and is classified as carcinogenic. In addition, cadmium (Cd) occurs naturally (from all phosphorous fertilizers and rocks). Cadmium can damage the kidneys, causing excess production of proteins in the urine – the duration and level of exposure to cadmium determine the severity of the effect. The excess uses of phosphorous and nitrogen fertilizers in the soil after AHD construction attribute to the spread of cancer in the different body organs of rural peoples and farmers.

4 Synthesis of AHD Impacts on Environmental and Ecosystem Sustainability

4.1 Environmental and Ecosystem Sustainability

Some impacts are much better understood than others are. The sweeping generalizations of the two groups, made primarily to justify their positions, for the most part do not survive scrutiny.

The environmental impacts and the cost of large dams on river ecosystems have received significant consideration and have become a major concern. Dams are designed to adjust the normal flow regime of rivers, and, as such, they have profound impacts on natural river processes both upstream and downstream from the dam.

The impacts of dams on river ecosystems are numerous, complex, and varied, some obvious and others more subtle, but all mostly have negative consequences. The environmental impacts of dams on river ecosystems can be observed within a hierarchical framework of first-, second-, and third-order impacts with upstream and downstream effects considered separately (Table 1) [22]. First-order impacts are the immediate abiotic effects on the hydrology, water quality, and sediment load of the river as a direct consequence of the dam. These are the key driving variables that lead to second- and third-order impacts resulting in long-term changes of the river ecosystem. Second-order impacts are the abiotic and biotic changes in ecosystem structure and primary productivity caused by first-order impacts that take place over several years. Third-order impacts are the long-term biotic impacts on higher trophic levels that result from the integrated effects of first- and second-order impacts. In general, the complexity of the ecosystem processes and their functions that are altered increase from first- to third-order impacts.

4.2 Complex Issues with No Single Answer

In the cacophony of arguments, what is often forgotten is that the issues involved are complex and that there is no single answer that could apply to all the dams of the world, constructed or proposed, irrespective of their locations and sizes. Nor can one view be everlasting in any country; it will invariably change with time. Some opponents to dam construction argue that building large dams is an environmentally unsustainable solution for generating electricity, flood control, and irrigation for the following reasons [22]:

1. The life span of a large dam is limited. Because of problems like sedimentation, most dams lose part or all their functions after about 100 years. In addition, turbid waters from the Ethiopian plain no longer reach the dam (Fig. 7). However, the impacts on the environment are irreversible and perpetual. Therefore, the short-term benefits of the large dams do not offset their long-term negative impacts.
2. Large dams alter the conditions of river systems so dramatically that many species cannot adapt appropriately and therefore are likely to go extinct. According to numerous studies, dam building is among the most harmful human-caused reasons for biodiversity loss.
3. The impacts of dam creation on the environment could act at different spatial scales and thus are challenging to assess. Many studies emphasize only on the local impacts, but dams may also affect the regional climate and geological conditions, such as triggering earthquakes, and could even contribute to global climate changes because of increased greenhouse gas emissions.

The proponents of dam construction do not essentially reject these negative impacts on the environment but often claim that they are exaggerated. They note that ecosystems have the capacity to adjust to the changes and that several technological approaches can be applied to mitigate the negative impacts. In sum, they

Table 1 A hierarchical framework of upstream (location in relation to dam) impacts of dams on river ecosystems [22]

Category of impact	Impact	Implications for AHD
First order	Thermal regime modification	The large mass of water impounded behind the dam tends to increase water temperatures upstream and modifies the thermal regime of the river downstream by changing the natural seasonal and short-term temperature fluctuations downstream
	Sediment accumulation in reservoir	All reservoirs accumulate sediments and lose water storage capacity over time, but the rate at which this happens varies widely. Due to sediment deposition, about 0.5–1% of the storage volume of the world's reservoirs are assumed to be lost annually [23], leading to reduced water storage capacity and hydro-energy generation potentials of the dams
	Water quality changes	The quality of water stored behind a dam can be very different from the river water that flows into the reservoir. Heavy metals, which are carried by sediments, tend to accumulate in the upstream inundation area of a dam. Changes in water quality of the reservoir will also impact water quality downstream. The salinization of water due to increased evaporation can be particularly problematic for downstream river ecosystems and floodplain wetlands [7]
	Evaporation and greenhouse gases	The amount of water evaporated from a reservoir (affect, e.g., water salinity) is associated with both the surface area of the reservoir and the climatic conditions which control potential evaporation, i.e., evaporation is greatest from reservoirs with large surface areas located in hot arid climates Emission of greenhouse gases, carbon dioxide (CO_2), and methane (CH_4), from reservoirs because of decomposition of submerged vegetation, has become a more concern. Shallow reservoirs are the largest emitters of greenhouse gases [7], with average flux rates of 3,500 mg CO_2 and 300 mg CH_4 m^2/day
Second order	Changes in channel configuration	Dam construction can greatly impact the landscape of the catchment area and morphology of the river channel with

(continued)

Table 1 (continued)

Category of impact	Impact	Implications for AHD
		resultant impacts on the hydrologic regime of the river [24]. Land use and land cover change are some of the most obvious impacts of dam construction on the landscape [25]. Dam construction on the Nile River has resulted in erosion rates of its Delta of up to 5–8 m year^{-1}, and in some locations, it reached as much as 240 m year^{-1}
	Increased growth of aquatic macrophytes, plankton, and periphyton	The changes of hydrology, sedimentation, thermal regimes, and water quality associated with dam construction and operation can impact the composition and biomass of aquatic organisms including phytoplankton, periphyton, macrophytes, and fish in the food web. Changes in the flow regime, water quality, river continuum, channel morphology, habitat conditions, and food webs may benefit some species, but they generally have an adverse effect on the majority of native species
	Reduced biomass and diversity of riparian vegetation	Riparian vegetation can be remarkably impacted by damming, leading to habitat heterogeneity, declines in species richness and native species, and exotic species invasion [26, 27]. Short-term vegetation changes are different from the long-term response due to riparian succession after dam begins operation
Third order	Changes in distribution and abundance of invertebrate, fish, bird, and mammal populations	Dams are believed to be not only a major cause for a decline in freshwater biodiversity, particularly the expiration of native fish species, the invasion of exotic fish species, and the decrease in fish beta-diversity, but also a major driver for the loss of terrestrial biodiversity along riparian zones
First order	Changes in the timing, magnitude, and variability of daily, seasonal, and annual flows	Flow regulation by the dam alters the intensity, timing, and frequency of downstream flow patterns reducing river discharge and flow variability by increasing low flows and dampening high flows. Downstream impacts are specific to each dam and depend on the storage capacity of the dam relative to the volume of river flow combined with how the dam is operated. In addition, the local climate

(continued)

Table 1 (continued)

Category of impact	Impact	Implications for AHD
		can impact flow regime patterns in dam area as well [24]
	Changes in water quality	Changes in water quality of the reservoir will also impact water quality downstream. Water released from a thermally stratified reservoir may change the natural temperature regime of the river, which impacts in-stream biota, because it influences many important physical, chemical, and biological processes [7]. In arid climates, the salinization of water due to increased evaporation can be particularly problematic for downstream river ecosystems and floodplain wetlands [7]. Elevated salinity also will affect aquatic organisms
	Reduced sediment flows	The reduction in sediment load tends to scour the channel below the dam, but the regulated flow regime (reduced peak flows) will counter this effect by reducing the flow velocity of the river. Both of these processes are modified by the erodability of the channel banks and downstream sources of sediments. Further downstream, increased sedimentation (aggradation) may occur because suspended material in the river water is deposited due to slower moving water resulting in a widening of the channel [7]
	Alteration of channel, floodplain, and coastal Delta morphology	Downstream of a dam, a reduction in sediment load can lead to increased erosion of river banks and beds, loss of floodplains, and degradation of coastal Deltas as sediment carried downstream by the river is no longer being replaced by material from upstream [7]
Second order	Change in plankton and periphyton assemblages	Downstream of a dam, primary production of phytoplankton, periphyton, and macrophytes are affected by changes in flow characteristics, water chemistry, turbidity, and thermal regimes. The flood mitigating characteristic of dams tends to promote the maintenance of higher than natural plankton populations within regulated rivers, by both sustaining populations released from the reservoir and promoting conditions for plankton development

(continued)

Table 1 (continued)

Category of impact	Impact	Implications for AHD
	Increased growth of aquatic macrophytes	Algal growth occurs in the channel immediately downstream from dams because of the nutrient loading from the reservoir releases [7]. Algal biomass was found to be up to 30 times greater downstream as compared to an upstream reference site with a very different species composition
	Change in riparian vegetation	Large dams can significantly change shoreline and riparian vegetation in both the impoundment region and downstream reaches, even though the critical environment processes and diverse habitats for flora and fauna are supported by the riparian ecosystems
	Change in channel, floodplain, and coastal characteristics	In addition, changes in sediment transport can result in changes in floodplains and even coastal Delta and coastline morphology hundreds of kilometers below a dam site. Dams can either increase floodplain deposition or decrease it by erosion depending on specific conditions [7]. In some cases, the reduced frequency of flood flows and the stable low flows associated with the dam operation may encourage vegetation encroachment that can stabilize new deposits, further trap sediments, and reduce floodplain erosion. In other cases, the increased peak flood flow associated with dam operation may increase channel bank erosion, resulting in the loss of floodplains [7]
Third order	Changes in distribution and abundance of invertebrate, fish, bird, and mammal populations	Downstream of dams and fish populations change remarkably due to blockage of migration routes, disconnection of the river and floodplain, and changes in flow regime, physiochemical condition, primary production, and channel morphology [7]
	Increased salinity of estuaries	The loss of additional water from evaporation can affect not only the water utilization efficiency by human beings but also the downstream ecosystem health, e.g., water salinity associated with evaporation in arid climates can damage downstream river ecosystems. Elevated salinity also will affect aquatic organisms

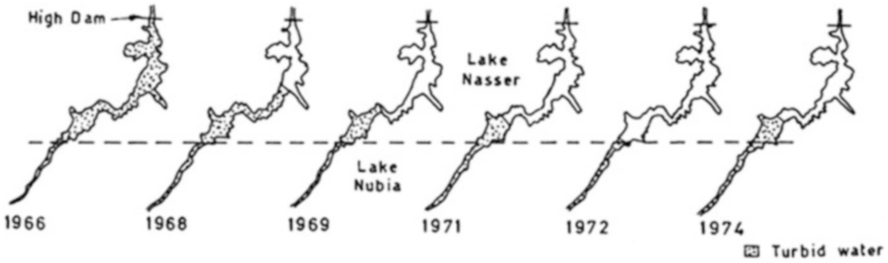

Fig. 7 Extent of flood turbid water in selected years

argue that there is still an overall advantage to society to building large dams, as their positive benefits outweigh the negative impacts. What has been forgotten in the current debate on dams is that neither the statement "all dams are good" nor "all dams are bad and thus no new ones should be constructed" is correct and applicable to all dams. Depending on the criteria of "good" selected, it has to be admitted that there are both good and bad dams.

A few important lessons may be learned. In terms of the basic aims of controlling river flow for curbing flood overflow, enlarging irrigation cropping, and boosting power generation, the high dam achieved its purpose. It did not, however, lead to an expansion of irrigated acreage. Most of the side effects were anticipated. With three exceptions, all of the apparent impacts as identified today were noted in some fashion and with greater or lesser accuracy at the start of the project. It was identified at the outset, the record of subsequent study is mixed, and it is difficult to ascribe relatively accurate or precise numbers to all. Some, such as silt load, reservoir fish, and evaporation, were monitored with relative care. Others, such as river fish and extent of irrigated land, were handled rather casually.

5 Mitigation of the Negative Impacts

However, the real question is not whether the Egyptians should have built the AHD or not – for Egypt realistically had no choice – but what steps could have been taken to reduce the adverse environmental impacts to a minimum.

When discussing the mitigation of negative impacts, there are always three categories to be considered, in the following order:

1. *Avoidance*: Measures (project modifications, choice of an alternative site, etc.) that will prevent a certain impact from actually happening, in many cases, lead to a yes-or-no type of decision. Because certain impacts can only be avoided if the project is not implemented; this, of course, should be considered as an option.
2. *Minimization*: Reducing the magnitude of an impact by applying adequate measures (e.g., reducing dam height and therefore reservoir size to limit the area to be

submerged or pre-impoundment reservoir clearing to reduce the impact on water quality).

3. *Compensation*: In cases where an impact cannot be avoided and adequate mitigation is not possible, compensation can be an acceptable solution. This would mean that the lost value is replaced by something of equal or higher value located elsewhere. Such a compensation would, for example, provide agricultural land of the same size and value to a farmer who loses his land because of a project or replace a loss in forested area by reforesting a similar area with a comparable forest type elsewhere.

5.1 Toshka Flood Escape

A major aspect of the AHD has been the need to relieve the floods threat in lower Egypt, in view of the damage caused by the high floods of the late nineteenth century. A large portion of the available storage was reserved for flood protection. Hurst [28] noted that there had always been the intention to reduce the flood volume by diversion or reservoir storage. Both banks of the Nile from Khartoum to Aswan had been searched for a suitable depression. The Toshka depression (Fig. 8), 250 km above Aswan, was investigated in 1972 as a potential site for a desert flood escape. Pilot studies of survey contour maps showed that a volume up to 120 km^3 could be stored in this depression, with a connecting channel about 30 km long from the reservoir. Its use was simulated over the high-flow period (1870–1899). It would avoid downstream flood flow and channel degradation and allow the storage for flood protection to be significantly reduced. It was estimated [29] that the construction of the Toshka flood escape could reduce the flood storage to 17.4 km^3 for annual control and increase the over year storage to 115.8 km^3.

The Toshka flood escape (Fig. 8) came into operation in the 1990s to convey water from Lake Nasser to the Sahara Desert through a synthetic canal. Between 1998 and 2002, a series of unusually high-volume floods of the Nile increased the water level of Lake Nasser/Nubia to beyond the capacity of the AHD. This problem prompted construction of a draw-down channel linking Lake Nasser with the Toshka depression adjacent to Lake Nasser. Flooding of the Toshka depression made four fundamental lakes with a most extreme surface area of around 1,450 km^2 – around 25.26 billion m^3 of water. By 2006, the amount of stored water was reduced by 50%. In June 2012, water filled just the lowest parts of the main western and eastern basins – representing a surface area of 307 km^2 or approximately 80% smaller than in 2002.

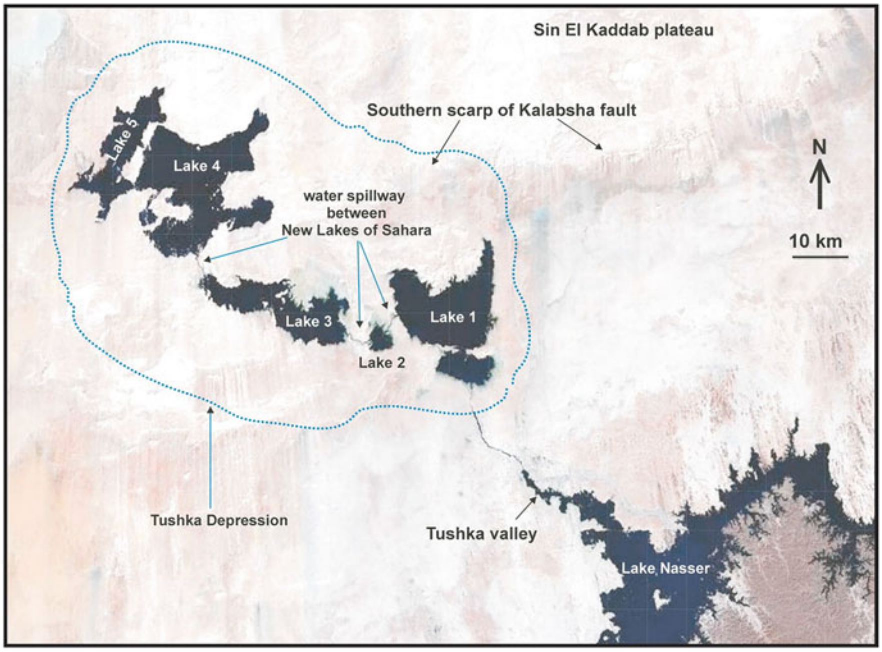

Fig. 8 Images of Toshka Lakes that created by the diversion of water from Lake Nasser through a man-made canal into the desert

5.2 Potential Fear of GERD Construction

By 2025, the country will face nationwide shortages at alarming rates. Decreasing freshwater supplies and the increasing salinity level of the Nile Delta's agricultural land threaten to make the country uninhabitable by 2100. Water shortages have been noted in some areas of Egypt in recent years. These changes attribute to the climate change effects and increased human activity near the Nile in recent decades, including the building of dams on the river in Egypt and in Ethiopia. Climate change can potentially change the water supply and demand patterns in the basin. Sharing of the already scarce water resources of the Nile River may become a serious security challenge in the near future. Not constrained by any water-sharing agreement with Egypt or Sudan, Ethiopia unilaterally developed plans to divert the Nile waters without considering its severe impacts on the live of the Egyptian. In spite of objections from Egypt and Sudan, Ethiopia maintained its sovereign right to develop the water resources within its borders. Economic and technological backwardness and political troubles had stalled the Ethiopian plans to develop Nile water for a long time. The amount of freshwater available in Egypt "may drastically fluctuate" in the coming decades due to factors like global warming and rising ocean temperatures, compounded by the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile.

The impacts of GERD project on AHD identified are reduction in the water share of Egypt, reduction in power generated at AHD, increase the salinization of Egypt's agricultural lands, increase the seawater intrusion, degradation of the environment among other identified impacts that presented in the other chapters of this volume, and infilling Lake Nasser/Lake Nubian with sediment. It is believed that the construction of GERD will affect the Egyptian quota. This effect on Egypt quota will decrease the Aswan High Dam (AHD) discharges [30]. The main adverse impact in Egypt will be a reduction in power generated at Aswan High Dam due to a fall in water levels of Nasser Lake. There may be a 50% decrease in the freshwater available to us. These figures are not yet confirmed (personal view), but there will be a great deal of variability and unpredictability. GERD construction will influence the flow of the Nile River to Egypt even further. This would make agricultural planning difficult or unsustainable in the future.

From an aircraft flying over Egypt (Fig. 9), it is easy to see the stark contrast between the green (red in the image) narrow strip of land that borders the Nile and barren desert a mere few 100 m away. Any threat to the flow of the Nile is a direct threat to Egypt's national survival.

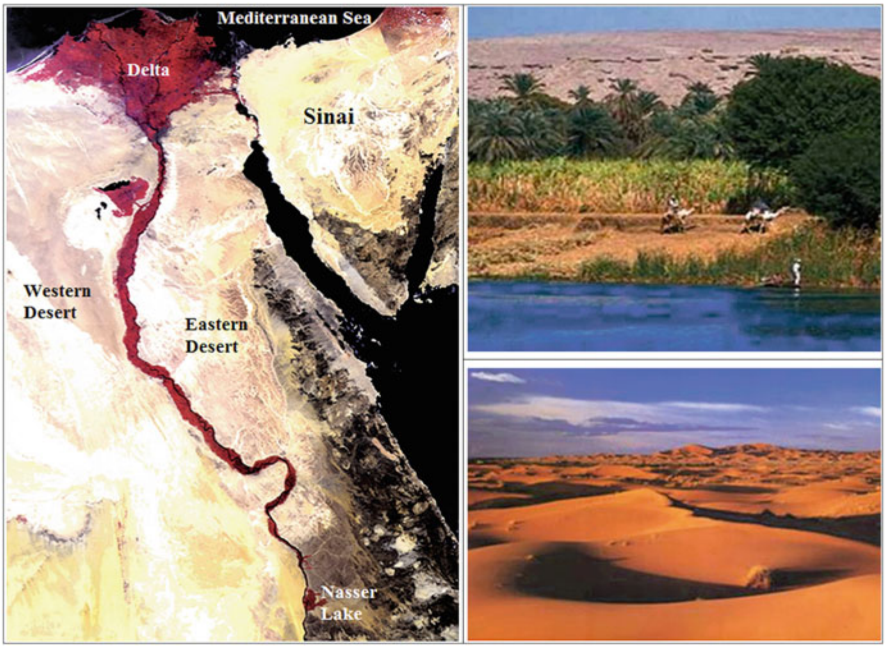

Fig. 9 The contrast between the green narrow strip of land that borders the Nile and barren desert a 100 m away

6 Conclusions

Since the 1950s, the Aswan Dam has been commonly referred to as the High Dam, which is larger and newer than the Aswan Low Dam, which was first completed in 1902. Following Egypt's independence from the United Kingdom, the High Dam was constructed between 1960 and 1970. The overall impacts of the AHD creation can be classified into four broad categories: physical, biological, economic, and social. Many of the impacts are often interrelated, and some of them may spawn effects of other types. It aimed to increase economic production by further regulating the annual river flooding and providing storage of water for agriculture and, later, to generate hydroelectricity. Before the dams were built, the Nile River flooded each year during late summer. These floods carried high water and natural nutrients and minerals that annually enriched the fertile soil along the floodplain and Delta. As Egypt's population grew and conditions changed, both a desire and ability developed to control the floods and thus both protect and support farmland and the economically important crops. With the reservoir storage provided by the dam, the floods could be lessened, and the water could be stored for later release.

Among the main physical impacts of the dam were the following: changes in the level, velocity, and discharge of the flow in the Nile River both upstream and downstream of the dam; increase in groundwater levels due to the introduction of year-long irrigation; changes in soil salinity and water logging; erosion of the river banks, beds, and Delta; sedimentation in the river and Lake Nasser; possible earthquakes; and reclamation of desert for human habitat and agriculture. The High Dam increases the coastal erosion at the Mediterranean Sea and made the construction of further expensive coastal protection works along the Nile Delta and beyond necessary. There were several major biological impacts, which included incidence of schistosomiasis, implications for fish production, and changes in flora and fauna. Among the economic impacts were generation of hydropower; increase in industrial activities and industrial diversification, because of the availability of electricity; increase in agricultural land, as well as crop intensification and diversification; and impacts on brick-making industry. There were several social impacts, which included peace and stability of the country due to increased economic activities and higher standard of living, eliminating the ravages of floods and droughts downstream of the dam, and resettlement issues.

We personally believe that the advantages of the Aswan Dam outweigh the disadvantages. We think that the disadvantages are aimed at selective groups like those that the Nubians all being moved although it is a large-scale thing and they were not happy, they were moved to better housing, into better education and healthcare. The advantages, however, help Egypt as a whole, their entire livelihood and economy, maybe not so much the environment though. Like electricity for homes and industry, almost everyone all over the country will benefit from cheaper electricity.

In the next 50 years, Egypt's coastal zone, home to more than 40% of the population, stands to be severely damaged by flooding, groundwater salinity, and erosion resulting from rising sea levels associated with global warming. Such a rise could potentially create as many as 14 million internally displaced persons with about 40% of all Egyptian industry located within the Delta area. Nile Delta's increasing salinity and rising sea levels may make Egypt uninhabitable by 2100.

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Importance of Aswan High Dam to Egypt

Nader Noureldeen Mohamed

Contents

Abstract River dams are generally constructed for several purposes such as: to generate hydropower; storing water for irrigation and for long-term uses during low flooding and drought years; and both for hydropower generation and saving water. The beneficial side effects of the river dams are to control the river destruction power during high flooding years, to prevent the siltation in irrigation canal, and finally to save water from being wasted in the sea. The collective benefits of Aswan High Dam

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(AHD) are increasing the Egyptian water resource, controlling and regulating floods, protecting Egypt from potential frequent droughts, increasing agriculture productivity, and completely regulating the river water. The benefits also include preventing siltation in the irrigation delivery systems, enhancing the agriculture extension and desert greening, changing the agricultural pattern to intensive and continuous cultivation, and increasing the cultivation area of high water-consuming crops such as rice, sugarcane, sugar beet, and green clover. The AHD dam is also responsible for generating 2.1 MW of clean sustainable and environmental friendly power, improving navigation and enhancing tourism which create Nile cruise ship hotels, transforming/alternating the agricultural pattern toward having more cash and export crops, increasing fishery and fish productions, and saving the Nile water from being wasted in the Mediterranean Sea. The dam also has a lot of positive economic effects that can help in improving some infrastructure issues as well as the quality of drinking water.

Keywords Agriculture, AHD, Collective benefits, Drinking water, Fishery, Flood, Hydropower, Irrigation, Navigation, Nile, Tourism

1 Introduction

River dams are constructed for several purposes: to generate hydropower, to save water for irrigation, dams for both hydropower generation and saving of irrigation water, to tame and control the flood destructive power during flooding season, to protect countries from potential frequent dryness or droughts, and finally to store water for long-term use during the drought seasons, in addition to saving the water from being wasted in the sea. Recently and according to the recommendation of the World Bank (WB) in 2003 [1] about the right of financing water and water trade, this will create a new market for selling water. This also will encourage some poor economies of the upstream river countries, which are rich in water resources such as Ethiopia, Democratic Republic of Congo, Burundi, Rwanda, and others to deal with water as goods available for sale within the next decades. The WB stated that water is an economic commodity, a social good, and an environmental good.

However, the purpose of constructing dams differs from upstream to downstream countries. In the case of upstream countries, it is mainly constructed for generating hydropower according to their high altitude, rough sloping, and plenty of cataracts and for changing cultivation from low-yield crops of rainfed agriculture to high-yield crops of irrigated and continuously intensive agriculture. On the other hand, downstream countries construct dams mainly for long-term or century water storing, irrigation, controlling water damage during flooding, and keeping water from wasting in the sea, in addition to regulating the water flow according to the demands of different life sectors, such as agriculture, industry, domestic, municipal, environment, and biodiversity requirements, and of course to generating electricity which will be here as a side product. The considerations of upstream countries when constructing a dam differ completely from those of downstream countries, especially causing significant hazards to the next downstream riparian countries. According to the "Convention on the Law of the Non-Navigational Uses of International Watercourses 1997" [2], dams of the upstream countries should be small and not cause significant hazards to the other former constructions on the downstream countries. Moreover, the upstream countries should conduct all studies about the environmental, socioeconomic, and hydrological impacts of the projected new dams and send it to the downstream countries before beginning its construction process to approve it within a year. On the contrary, the downstream country should conduct the same studies but to its internal affairs. For example, the Great Ethiopian Renaissance Dam should have an accurate study about its environmental, socioeconomic, and hydrolytic impacts on Sudan and Egypt, but the Aswan High Dam in Egypt has no impacts on the other riparian countries because it just regulates and controls the river water inside Egypt at the end of its journey. Moreover and according to the extensions of the man-made dam lake inside the Sudan lands, Egypt should get the Sudan approval and have a share of benefits from this lake; otherwise the interior dams in any downstream country never cause any hazards with the riparian countries.

2 Why Is Hydropower the Most Attractive Option?

The Nile Basin Initiative [3] reported that the cost of generating electricity from different sources is not by 8.06 American cent for hydropower and 7.32 for the geothermal, and the maximum for the heating methods by oil products ranged between 21.85 up and not up to 30.17 for the light and heavy oil, respectively, at an oil cost that ranged between 100 and 120$ per barrel. Thus, the hydropower options have the priority in the Nile basin region according to the following [3]:

- Having a long economic life which translates to a very low per unit cost of energy.
- A renewable energy source with proper preparation of the reservoir is pollution free and eligible for carbon credits.
- Responding quickly to changing power system conditions and enhancing stability and reliability of supply.
- Providing cost-effective means for storing surplus energy from nonconventional renewable sources of energy such as solar and wind, which are by nature intermittent.
- The high need for intensive labor which provides huge employment opportunities during construction and operation which are very important for developing countries.
- Delivering additional benefits through the dams, such as flood control and river flow regulation, irrigation, transport and navigation, aqua farming, recreation, and industrial and domestic water supply.

- They are usually accompanied by auxiliary infrastructure projects such as roads, electrification, telecommunication, schools, health centers, and other government services that provide added benefits to rural communities.

3 Egypt Before Aswan High Dam

Egypt is not a rainy country and belongs to hyper-arid and arid regions. That means Egypt counts only on irrigated agriculture by using its only river as downstream Nile River country.

Before construction of the Aswan High Dam (AHD), the annual water flow was variable from year to year, but after the dam completion (1971), the water flow in the Nile, throughout the year, becomes stable and accurate according to the actual requirement of the three main sectors (municipal, industry, and agriculture in addition to environmental protection requirement) in both winter and summer seasons. The reservoir water stored in the front of the Dam on its lake became available for release at any time during the year according to the maximum demands of different economic activity sectors. Moreover, the Nile flooding that happens on a regular basis is repeated seven times every 20 years (the Nile cycle before climate change was 7 years high flooding, 7 years low flooding plus drought, and 6 years in average); these floods used to almost destroy all the villages in the Upper Egypt governorate causing severe erosion to the fertile alluvial agricultural lands and then pond all the delta lands for almost 4 months from July to October every year. That means that there are only the early summer crops that must be harvested before August (starting cultivation from April to late July or early August).

After the flooding water from agriculture lands is withdrawn, farmers are starting to plant their lands by different winter crops especially wheat, green forage, bean, lentil, chickpeas, etc. These cultivations rely and count on the flooding water stored in the root zone and soil profile without any needs for irrigation during the plants' growing period. This pattern of agriculture is called "basin agriculture." Thus, Egypt before AHD cultivates their alluvial lands only one time a year from October to November up to July to August. Egypt now cultivates all their alluvial lands in the Nile valley and delta three times a year and may be four times a year for some vegetables.

However, Egypt relied most on White Nile water during the period from January to July every year which the farmer called "fire period" that means the period of little water that is not enough to firefighting the thirsty lands. This period was barely enough for agricultural and domestic uses. During this period, there was a restriction on the use of the little White Nile water by Sudan according to 1929 agreement between both of Egypt and Sudan in one side and the main White Nile countries in the other side (Kenya, Tanzania, and Uganda), which were under British administration (colonial).

The 1929 Nile water agreement stated that Sudan could take water from the river and its tributaries inside the Sudan border as follows [4]:

- From July 15 to August 31, without limitation
- From January 1 to February 28, enough to irrigate 38,500 feddan
- From March 1 to July 15 enough to irrigate 22,500 feddan

The agreement of 1929 did not define water right in quantitative terms, but the 1920 report of the Nile Project Commission suggested that Egypt should be guaranteed sufficient water to the maximum acreage cultivated up to that time, which was five million feddan. It is on the basis that quantitative estimates were derived that gave Egypt acquired rights to 48.5 BCM/year.

4 Collective Benefits of AHD

4.1 Increase Water Share of Egypt and Sudan

According to the agreement of 1959 between Egypt and Sudan to get the Sudan approval to construct the AHD, the two countries agreed to increase the Egyptian water share from the Nile to 55.5 BCM/year instead of 48.5 BCM (according to 1929 agreement). It also increased the Sudan quota to 18.5 BCM/year instead of 4.5 BCM. The agreement has been refused from all other Nile basin countries especially Ethiopia and their emperor Haile Selassie, which considered it illegal and just a bilateral agreement between Egypt and Sudan, not approved by other Nile basin countries. Moreover, Ethiopia, Tanzania, Uganda, and Kenya accused Egypt and Sudan of the dominance of the Nile water away from the other riparian countries.

The total Egyptian population in the year 1970 was almost about 37 million capita [5], and the shared water per capita/year from the Nile water was 1,500 m^3. The situation in 2017 became more severe (harder) than before. The total population has increased to 104 million (officially). The shared water per capita accordingly has decreased to 600 m^3 (55.5 BCM from Nile +5.5 ground water +1.3 rain = 62.3, over 104 million of the population) below the scarcity level. However, the AHD saves great amounts of water from being wasted in the sea during the August–October period, through the flood period which is estimated by 22 BCM layouts into the Mediterranean [6].

4.2 Control River Floods and Protect Infrastructure

One of the most important benefits of the AHD is its role in saving Egypt from extreme floods that destroy all villages and its infrastructure in Upper Egypt and cause severe damages in the Lower Egypt (Delta) during the inundation due to the high floods. These severe floods were repeated before and after AHD for years (1964 and 1975 and from 1988 to 1994) [7]. It also protects the fatal infrastructure such as electricity cables, drinking water and communication lines, roads, houses, and factories from the frequent regular damages during rough flooding years in addition to saving the life of thousands of people. For example, in 1946, before the construction of AHD, the flood damages were about 70,000 feddan, while in 1964, during its construction, it protected Egypt from the damage of about 100,000 feddan which were estimated by a value of 10 million L.E [6, 8]. Negative impacts of Nile floods can be concluded in the following [9]:

1. Cause severe damage to agricultural infrastructure (fixed capital, canal, bridges, pumping stations, etc.), which will not be modeled.
2. The high or early flood highly obliged the farmers to make early harvesting which means a premature yield crop of the summer season, reducing yield in both quantity and quality.
3. Cotton and maize were the main crop hazard from flooding because it should stay until October, and the flooding begins in July.

4.3 Protects Egypt from Frequent Drought

Egypt is located in the driest and the high-temperature area in the world as seen in Fig. 1. The climate of Egypt ranges between hyper-arid and arid with average rainfall as low as 20 mm/year [10]. Thus Egypt belongs to the hyper-arid and arid region with almost no rain, and therefore, the agriculture in Egypt relies primarily and for the most part on irrigation all around the year. From the total water resources of

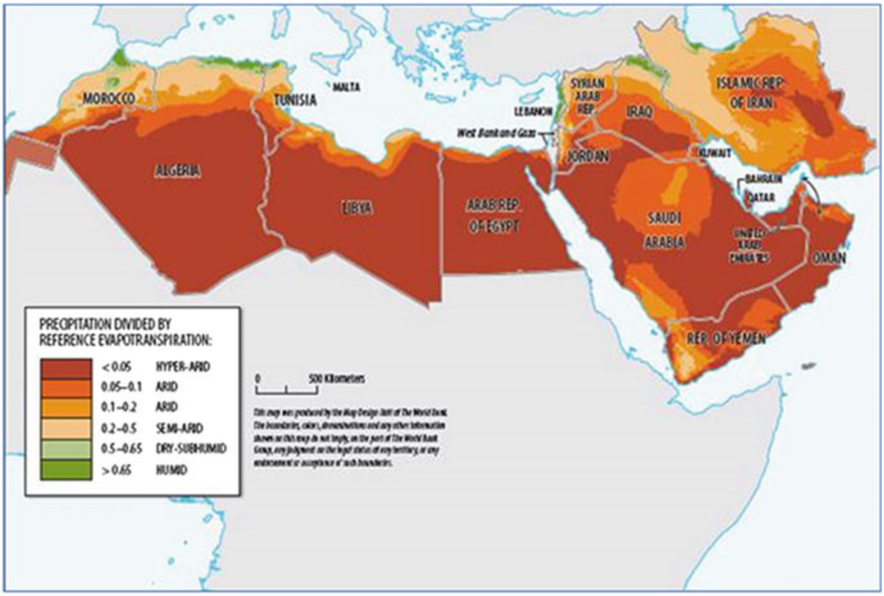

Fig. 1 Aridity zoning in Egypt and Middle East countries [10]

Egypt, there is only 5.5 BCM from deep groundwater and 1.3 BCM from rain, which means that Egypt relies mainly on Nile water with a quota that has regularly reached to remove to its border since thousands of year of 55.5 BCM.

Since the Pharaohs' era, Egypt has always been known as an agricultural country even with its dry warm weather, which means that food production consumes much more water than that in the cold or rainy countries. Accordingly, Egypt counts on every drop of water from the Nile River and knows very well that every drop counts. The Nile River represents more than 90% of Egypt's total water resources. During drought years of the Nile, the water discharge of the Nile River decreases by almost 50% or more and becomes as low as 44 BCM/year instead of 84 BCM. The frequent repetition of drought in the Nile basin within the last 45 years killed millions of people in Sudan, Kenya, Tanzania, and Ethiopia, with no death in Egypt due to the high reservoir of the stored water in lake of HAD during the high flood years and due to the role of HAD in regulating Nile water.

Aswan High Dam saves Egypt from a severe drought which happens on a regular basis of seven times every 20 years. The drought years extended and continued for 7 years from 1981 to 1988. These phenomena were repeated during the 11 years from 2006 to 2017. Most scientific studies predicted this long drought due to the effect of climate change and the "EL Nino-Southern Oscillation (ENSO)" in addition to the effect of EL Nino heat wing that hits the African corn recently. The low Nile water discharge below the average caused 13 drought cycles in the last 40 years, and frequently repeated in 1972, 1976, 1983, 1985, 1987, 1991, 1997, 1999, 2002, and 2010, because of the drought that hits East Africa [11]. Figure 2 shows the interannual variability of the Nile discharge from the year 1900 to the year 2002.

4.4 Increase Agricultural Productivity

Since the year of 1960, Egypt has been suffering from a deep food shortage and from threats from some food exporter countries especially the USA to banning the export of food to Egypt especially wheat, flour, poultry, and red meat (as what happened). This happens after a political dispute between Egyptian president Nasser and US president Lyndon Johnson in the year 1964 to ban the wheat export to Egypt except after cash payments. This matter pushed Egypt to think seriously about mitigating the food shortage by increasing the cultivation area and greening the desert and also increasing yield crops from the soil units in old lands (horizontal and vertical extension). The performance is considered as the most important benefit of the construction of AHD. The intensive and continuous cultivation of all agricultural land in both Upper and Lower Egypt without fear from the Nile flooding or a long drought conserves and increases the agriculture productivity to almost double the rates. The summer crops were the main benefactors from the dam because they used

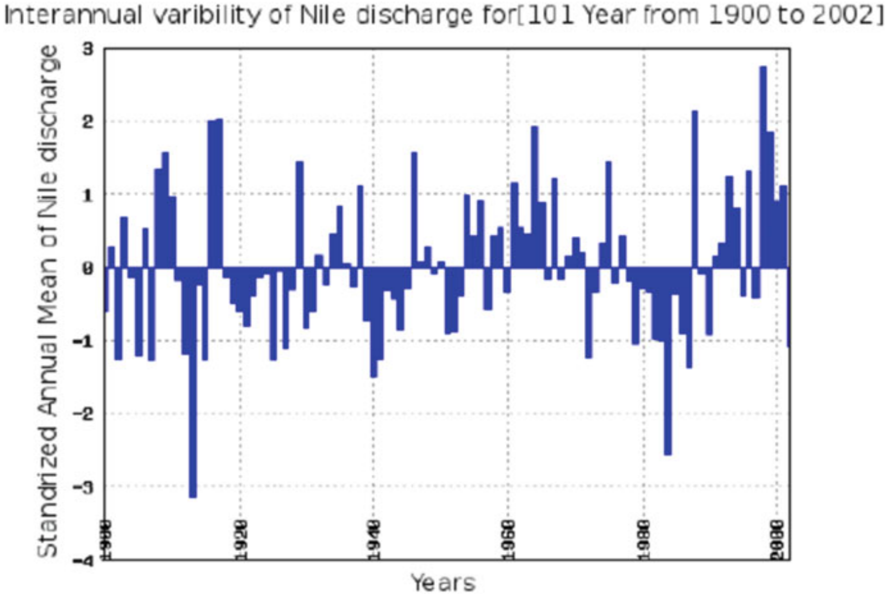

Fig. 2 Interannual variability of the Nile water floods within 100 years [11]

to suffer from the flooding season (July–November), and that added economic value to the Egyptian GDP [6, 8, 12]. The next table shows the cropped area of some essential crops in Egypt before and after HAD, which reflects increases in cultivation area of wheat, rice, sugarcane, and maize.

President Nasser began an ambitious plan for land reclamation to add two million acres to the old soils. Nasser began with a projected area located south of Alexandria Governorate and give it a sounded name related to his believes called “Moderiat El-tahrir which means liberation directorate.” The following president “Anwar El-Sadat” continues Nasser’s effort in greening the adjacent desert area in Nubaria eastern Alexandria, and that opened the door for the private sectors to reclaim some similar desert area in eastern delta in Sarkia Governorate. Thus Egypt reclaimed more than two million acre (841 thousand ha) after the AHD because of the water stability and the need for producing more foods (Table 1).

4.5 Regulate the Nile River Stream

One of the biggest problems of Egypt before AHD is the unsteady regulation of the river water. The situation before AHD was that of abundance, and there was a presence of plenty of Nile water from June to December that comes mainly from Ethiopian sub-basin especially from the Blue Nile and Atbara Nile where this

Table 1 A cropped area in some essential crops before and after AHD [12]

Crop	1960 (1,000 acre)	1995 (1,000 acre)
Wheat	1,387	1,829
Maize	1,727	1,906
Millet	469	346
Rice	799	1,276
Cotton	1,751	884
Sugarcane	122	274
Total	6,255	6,515

sub-basin provides 85% from the Nile water and 100% of flooding water. On the contrary, the low water from February to May mainly delivered from White Nile River comes from the sub-basin of great equatorial lakes which represent only 15% of the total Nile water discharge. This phenomenon is well known around Egypt by “the fire period” or the fire of arable lands due to the water shortage. After the AHD both of water coming from the two sub-basins become stored in the front of AHD in addition to the flooding water coming mainly from the Ethiopian highland rivers making a huge reservoir. The AHD had been regulating and controlling daily, monthly, and yearly water discharge downstream of the dam to meet the actual water demands instead of it being abundant in the last 4 months and four others of low water discharge, as shown in Fig. 3.

4.6 Prevent Siltation of the Irrigation Canal Net System

The sedimentation of irrigation delivery canal along 35,000 kilometer in the Delta and Nile Valley lands was a heavy load problem according to the great volume of siltation which comes mainly from Ethiopia through Blue Nile and Atbara Rivers that ranged between 130 and 160 million tones/year as shown in Fig. 4 [13, 14]. This problem costs Egypt before construction of AHD millions of pounds and thousands of workers to remove the precipitated mud from the irrigation canal and keep the canal on its full water capacity. The AHD – as all river dams – prevents the silt from passing through the regulated water stream from the front of the dam to the gate of it and then to the irrigation canals. The silt accumulation usually precipitates in the mouth entrance of the dam lakes and the first kilometers long of the lake. The siltation phenomenon in the irrigation canals obliged the Egyptian government in the year 1942 to establish a new special program called “winter sudd – or winter embolism.” The Ministry of Irrigation and Public Works (the old name of Ministry of Water Resource and Irrigation) stops water delivery to the irrigation canals for 1 month every year, during the cold and rainy month (end of January) especially in the delta regions that have more than 80% of the irrigation canals of Egypt (4.5 million acres instead of only 2 million acres in the Upper Egypt governorates), to have a chance to remove the high amounts of silt particles deposited in the irrigation canals.

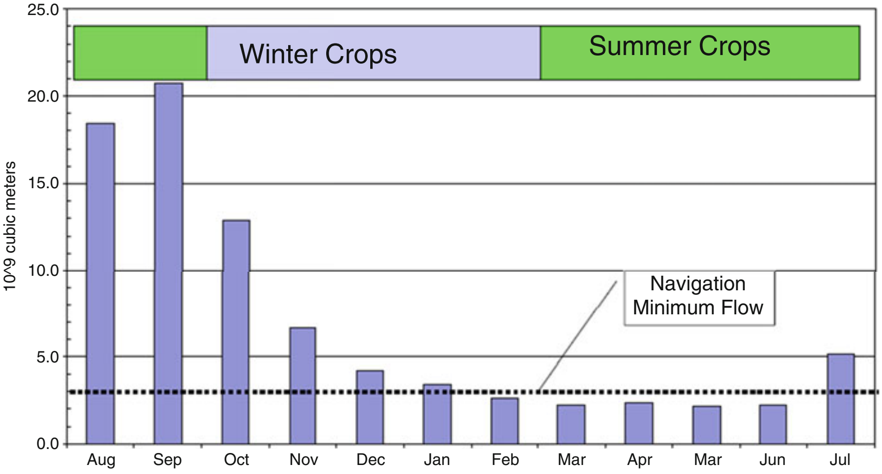

Fig. 3 Nile flow and growing seasons (mean monthly flow at Aswan) [12]

Fig. 4 Sediment excavated from the canal [8]

4.7 Increase the Agriculture Extension and Greening the Desert

Egypt is characterized by small cultivation area as a small narrow line at the Nile's two banks. The cultivation area does not exceed 6.1 million acres from the total Egyptian area of 238 million acre (3.5%). Egypt also suffers from a deep gap of food insecurity that reaches 60% of the essential food. Thus, Egypt needs to perform ambition plans to increase its limit of the agricultural area through extending in the wide desert (93% of Egypt area). The AHD helps Egypt support its plans for land reclamation and greening the desert, especially in the alluvial soil fringes to add almost of 2.5 million acres during the last 50 years and the cultivation area becoming 8.6 million acres. In fact, these newly reclaimed soils are not considered as an addition of new agricultural lands because it just replaced the fertile area loss by encroachment on the cultivated lands and settlement extensions in rural areas during the last six decades. Most of the land reclamation projects are located in North Egypt on the delta fringes. These extensions are located mainly in western delta desert extension and a small amount in eastern delta desert extension in addition to some swamps and wetland area in the Mid North delta south El-Burullus Lake of the Mediterranean Sea. The reason refers to the convenience of good weather in North Egypt for planting most essential crops with low evaporation rate and less water consumption than Upper Egypt [6, 10–12]. Most of the extension arable lands are sandy calcareous soils, except the soils of the Middle North Delta, which are wetland, swamps, sodic soils, saline soils, and waterlogged soils. Figure 5 shows the old lands and the newly reclaimed soils after AHD.

4.8 Cultivate the Nile Valley and Delta Lands All Around the Year

Before construction of AHD, the agriculture land used to be flooded and submerged due to the inundation of the Nile water for 3 or 4 months every year. The flooding water would saturate the full soil profile up to 1.5 m depth, and the soil becomes oversaturated with water. When the Nile flooding begins to withdraw from the agriculture land which usually happens in late October and early November, the farmers start to plant the winter seeds in the saturated soil. The seedling and growing plants rely on the stored water in the soil profile and root zone. This planting way is called “basin agriculture” which does not need to be irrigated or watered during the next 6 months until harvesting occurs in May just before the beginning of the next floods.

The constructions of AHD dam have changed this system of “basin agriculture” to new effective perennial and continuous irrigated agriculture especially in Upper Egypt and in most of the delta lands. The yield of the Egyptian cultivated lands has been almost becoming duplicated to 2.5 times the cultivated area during the year. The total cropping area (summer and winter seasons) was only 9.3 million feddan in the year 1952 before construction of AHD and has increased to be 14 million feddan in 1997 [13] and has recently increased again to be 19 million feddan according to cultivating crops twice or tripartite a year.

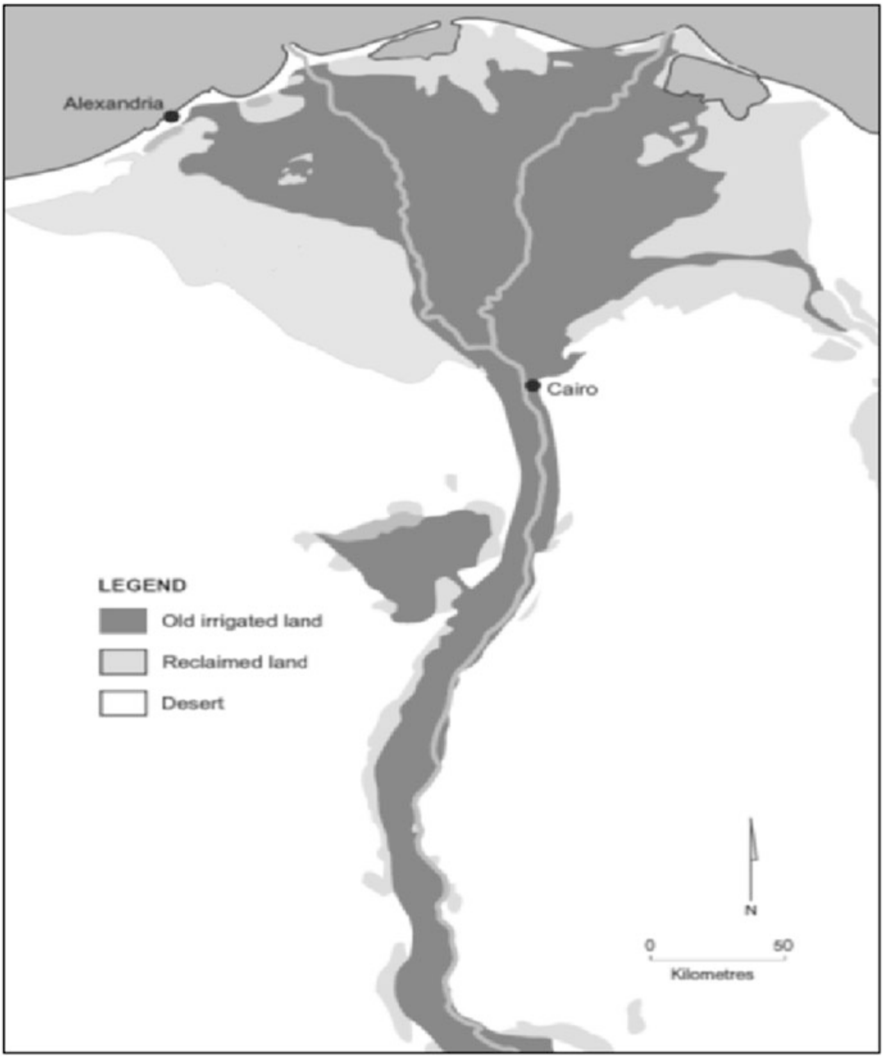

Fig. 5 The old soils and reclaimed areas after AHD in 2007 [12]

4.9 Doubling the Cultivation Areas of Rice and Sugar Cane

The abundance of reservoir water stored in the front of AHD reservoir helps to increase the cultivation area of high water-consuming crops, which is considered as strategic for needed foods in all family dining tables. This cultivation of these crops includes rice, sugarcane, sugar beet, clover as a forage crop, wide-leaf vegetable (cabbage, taro), and banana, to reach 100% of self-sufficiency from these crops.

After the construction of AHD, the percentage of self-sufficiency from rice has risen from 100 to be 150%, and Egypt becomes a rice exporter country for about three million tons/year. The self-sufficiency of sugar from sugarcane and sugar beet has increased to be 68% in addition to increasing the cultivation area of green forage such as cover and alfalfa (Egyptian species gives five cuts of green forage) needed to feed the livestock population to increase the red meat and poultry production. The total cultivated area of the rice crop was only 200,000 feddan in 1952 before AHD, but it is planned to be 700,000 feddan after AHD [13, 14]. The actual cultivation area has increased nowadays to two million acres, duplicating the yield crop per unit of lands which has become four ton/acre, instead of having this yield before AHD. The same trend was repeated with sugarcane, which used to have a cultivation area of 92,000 feddan in 1952, but it reached 275,000 after the dam [14] and had increased again recently to be 350,000 feddan in 2015 with a yield rate of 50 tons/acre, which was only 25 tons/acre before AHD. The sugar beet area has now reached 500,000 thousand acres instead of nothing before AHD.

4.10 Increase the Access to Electricity

The access to electricity in Egypt in the year 1959 was very low according to the weak economy and low GDP. Egypt pursued the search for an inexpensive and sustainable source of electricity generation that is always and obviously found in hydropower generation. One of the main objectives of constructing the AHD is to generate cheap hydropower. The Aswan High Dam turbines generate 2.1 MW/year, which increases the percentage of accessible electricity in Egypt, especially in rural areas and villages, also, to complete coverage of all cities [14].

Before the dam became operational, Egypt had to import fossil fuel. The electricity generated by the dam reduced in a most significant way the potential energy import bill of the country. Figure 6 shows the contribution the dam has made to the generation of electricity in the country. Up until 1979, the dam contributed to nearly half of the electricity generated in the country. The HAD hydropower plant began generating power at that time with an output of 71 MkWh in 1967 and gradually increased production to about 3,700 MkWh in 1972 against a total power generation in Egypt of 7,400 MkWh, i.e., about 50% of total power generated at that time [6]. This new hydropower increased the access of electricity and covered the electrification of more than 4,500 new villages. In some years, its share was significantly more than 50%. As time progressed, and especially after 1980, the dam’s share began to decline because of increased contributions from newly constructed thermal power plants which met the burgeoning electricity requirements of the country [15, 16].

The amount of hydropower produced by AHD currently only represents about 8% of all Egyptian demand, instead of 50% in the year 1979 (the total demand in 2017 reached 30,000 MW). This percentage was 50% of all Egyptian demand in the year 1970 which encouraged internal and foreign investments in the industrial

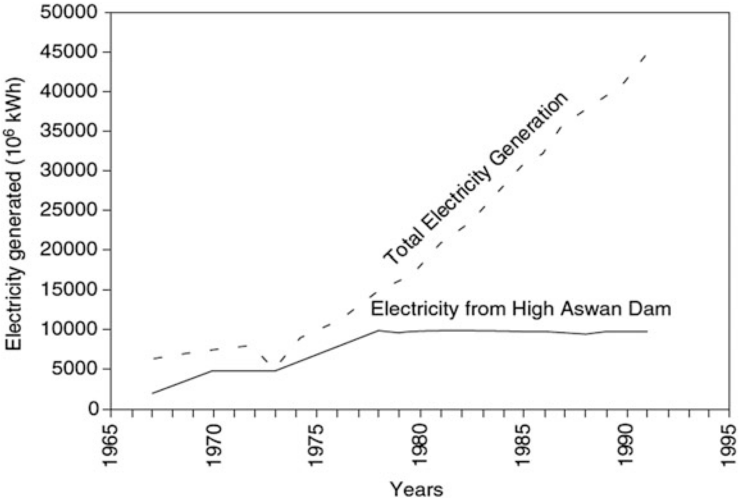

Fig. 6 Contribution of AHD to Egypt's electricity generation [15]

sectors. This step increased the number of factory works in Egypt in different fields: cement factory, chemical fertilizers, pesticides, iron and steel, car industry, agro-industry, sugar factories, chemical and oil refinery, textile, electricity equipment, etc.

4.11 Improving Navigation and Enhance Tourism

Aswan High Dam improved the navigation condition in the Nile course after the preventing siltation from the Nile runway and increase the amount of stream water that delivery to the downstream flow inside Egypt. In most of the recent improvements, there are no longer interruptions of freight movements because of low or high river flows [17] (see Fig. 7). The maximum fluctuation in water level has decreased from 9 to 3 m. This phenomenon was attributed to improved discharge to reduce flooding [18], although that benefit is countered in irrigated areas by continued overuse of high dam supplied water. Less frequently mentioned is the training that thousands of Egyptians received during the construction of the high dam as well as the national pride associated with the dam's completion and the development that followed.

The Aswan High Dam has improved navigation up and down the Nile all year round after controlling and regulating the Nile effluent. Ministry of water resources and irrigation delivers 3 BCM/year for navigation. This helps Egypt to establish the Nile cruise hotel navigation especially in Upper Egypt between Aswan City and

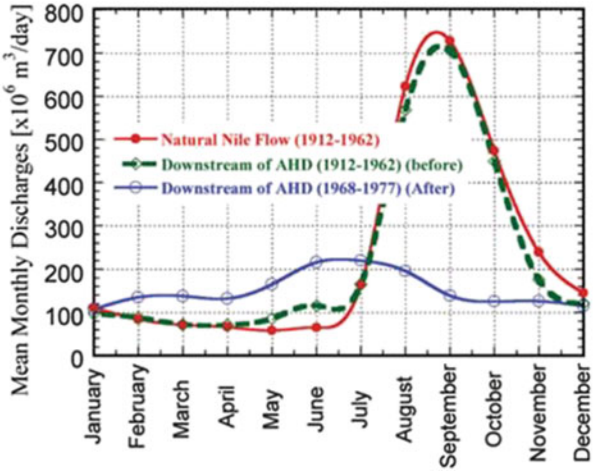

Fig. 7 Mean monthly flow of the Nile River in Egypt before and after AHD [19]

Luxor Town, because Luxor contains one-third of all global historical monuments and has a highly attractive correspondence of tourists (attraction power). This also established several navigation restaurants across the Nile especially in capital Cairo and Giza City which increase upcoming tourist. The annual number of tourists to Aswan has risen from 80,000 in 1960 to about 300,000 in the year 1997 [6] and to one million in the year 2010.

The Aswan High Dam, allowing year-round navigation up the Nile, has led to major investments in Nile River cruises as well as Lake Nasser cruises. In 2000, tourism accounted for 4.4% of GDP. A rough estimate is that 25% of tourism is Nile related. Hence, if the water flow in the summer falls below 18 BCM/year, then navigation is disrupted for half of the year. This leads to the loss of more than 12% of tourism. Also in very high flood years (more than 81 BCM), tourist sites are flooded (especially places in Luxor and the Valley of the Kings), accordingly, another 12% loss to tourism [19].

4.12 Restructuring the Agriculture Pattern to More Cash Crops

The continuous presence of water in Nile River and its branches all around the year after the construction of AHD without fearing from drought or floods encourages farmers and traders to change the cultivation pattern and transfer to cash and export crops. The cultivation area of the vegetable and fruit crops increased sharply, and Egypt accordingly became one of the biggest exporter countries for onion, tomato, potato, garlic, orange, mandarin, and other citrus crops in addition to leather production due to the increase of livestock population and planting more forage areas. Egypt nowadays exports almost 47 species of agriculture and food products to the EU countries and several others to all worldwide countries. Before the AHD, Egypt relied mostly on exports of fine and long cotton fibers.

4.13 Increase Fishery and Fish Production

As all the Mediterranean Sea countries, fish represent an essential food and low-price protein. Before the AHD, Egypt imported almost 60% of its needed fish mainly from Russia and Morocco. The Lake Nasser which is considered as the second man-made freshwater lake in the world, which was created after the construction of AHD, extends for 500 km long between Egypt (350 km) and Sudan (150 km). Moreover, the presence of water in the Nile all around the year caused a good increase in fish production in Egypt. The total annual fish catch from Lake Nasser in 1968, as expected during its initial years, was quite low at about 2,662 metric tons. The catch steadily increased from that time and reached a maximum of 34,206 metric tons by 1981. Records indicate that 1980–1983 were the most productive years when the annual fish catch varied between 28,667 and 34,205 metric tons. After that, the catch began to decline. The total annual catch fluctuated around 20,000 metric tons between 1993 and 1998 [17–19].

Recently, a problem between the government and the fisher community about whom should bear the cost of the fry (small fish) that should frequently supply into Aswan High Dam Lake and river stream inside the country, caused a sharp decrease in open fishery from fresh water, and river, the open fishery decreased, and the country transferred to an aqua fish culture which represents more than 65% in 2017 of the total fish production. Egypt has become the biggest country in Africa in aquaculture fish production. Even these aqua fish culture producers rely on the Nile and agricultural drainage water available all around the year after AHD. This also helps to create more jobs and improves the living conditions of the fishery society.

4.14 Save the Nile Water from Being Wasted in the Mediterranean

Before the construction of the Aswan High Dam, Egypt lost 22–34 BCM/year of Nile water outlet in the Mediterranean throughout the flood period from August to November, with the maximum peak in September. The average total of freshwater being lost in the seawater in 5 years (1959–1963) was 170 BCM, [9, 17–19]. The discharge of such a large amount of water during a relatively brief time was followed by a great change in the hydrography and biological economy of the southeast sector of the Mediterranean Sea.

With the reservoir storage provided by AHD, the floods could be lessened, and the water could be stored for later release.

4.15 Economic Value of the High Aswan Dam

Freshwater is the backbone of all economic branches such as agriculture, industry, housing, and others. Increasing water supply for these sectors means increasing the productivity and creating a strong economic base. According to [9, 20], the HAD adds high economic values of the Egyptian GDP. The total risk neutral benefit of the High Aswan Dam is estimated at LE 4.9 billion. The impact of a capital shock in agriculture and transport is LE 1.1 billion. The risk premium (for the standard assumption of a logarithmic utility function) is LE 1.1 billion. LE 7.1 billion is 2.7% of GDP in 1997, 15% of which is due to risk aversion. However, with a very high-risk aversion, the share of the risk premium goes up to 43% and the total benefit of the High Aswan Dam to LE 10.3 billion or 4.0% of GDP [20].

Moreover, according to the detailed cost-benefit analysis carried out by the Egyptian Ministry of Irrigation, at the time of the dam's construction, its total cost, including subsidiary projects and the extension of electrical power lines, amounted to Egyptian £450 million [8, 19]. These costs seem to be realistic since they are somewhat similar to World Bank estimates. The then irrigation Minister, Abdul Azim Abul-Atta [8], estimated that this cost was recovered within only 2 years, since the dam's annual return to national income was estimated at E£255 million, consisting of E£140 million from agricultural production, E£100 million from hydropower generation, E£10 million from flood protection, and E£5 million from improved navigation. Detailed estimates of these costs were prepared by the Egyptian government, and since no one has challenged them, one can be assumed to be reliable. Thus, our focus has been to assess appropriate impacts, especially environmental and social, about which there has been considerable global controversy ever since the construction of the dam was initiated. Nowadays, and from my accumulated experiences, the feedback (return back) of each single cubic meter of water in agriculture sectors ranges between 5 and 10 Egyptian pounds, 50 LE from industry, and 500 LE from tourism and hotels. Thus Egypt may gain up to 570 billion Egyptian pounds from the agriculture sectors which consume almost of 56 BCM/year, in addition to another 250 billion from the industry sector which consumes 5 BCM/year with good return back from hotels and resort sector.

However, the importance of the dam to Egypt's economic survival was demonstrated, at least qualitatively, during the 1980s. It is not too difficult to hypothesize what would have happened to the Egyptian economy and sociopolitical conditions if the dam had not been there to protect the country from, first, the potentially catastrophic impacts of a prolonged drought from 1979 to 1986 and immediately thereafter the abnormally high summer flood of 1988, which had devastating effects on Egypt's upstream neighbor on the Nile basin, Sudan. Even with the Aswan High Dam in place, Egypt had come perilously close to experiencing the catastrophic impacts of the drought by early 1988, due to a dangerously low water level in Lake Nasser [21].

4.16 Infrastructure and Drinking Water

In general, sediment is a pollutant by its nature. Even where sediment is uncontaminated by agricultural fertilizers and pesticides and industrial or human waste, they cause high turbidity in water which limits light penetration and prohibits healthy plant growth on the riverbed. The accumulation of sediments on the riverbed can smother or disrupt aquatic ecosystems by reducing food sources and degrading spawning grounds (such as gravel and rocky environments) and the habitats of desirable fish species. Turbidity may also result in eutrophication where nutrient-rich sediments are present (particular sediments from agricultural land with high fertilizer contents). Eutrophication creates a situation where the oxygen present in the water system is reduced to the point where fish species may be unable to survive in the water column. Eutrophication, where it results from toxic algal blooms, can also be a serious risk to human health [14].

Sediments in areas with high human activity often contain chemical pollutants which may pose a risk to human health and the health of surrounding ecosystems. Potable water supplies can be compromised by the presence of excess sediment (whether contaminated by toxins or not) as purification facilities may not be able to cope with the sediment in the water – leading to temporary breakdowns and subsequent risks to the safety of the drinking water. Contaminated surface waters also risk altering the metabolic processes of the aquatic species that they host. These alterations can lead to fish kills or alter the balance of populations present. Other specific impacts are on animal reproducing, spawning, egg and larvae viability, juvenile survival, and plant productivity. Some areas have been very active in improving water quality in relation to sediment management and control [14].

Sediments have impacts on other man-made infrastructure. Too much sediment can disrupt the normal functioning of irrigation pump station intakes and can also disrupt irrigation when excess sediment is deposited in canal systems. Deposition in canal systems can lead to high costs for those reliant on these systems as a water supply. Dredging may be required to remove surplus sediment. Sediment deposition may also result in blockages or inefficiencies in irrigation infrastructure (including pumps and distribution networks) and may even impact upon the produce. Sediment also has negative impacts on domestic water supplies – causing problems in both water treatment plants and distribution networks. Failure of water treatment plants, especially in poor regions, can mean that water is unsuitable for drinking. Populations may suffer from health effects as a result. In the Nile River basin, for example, the turbidity during the flood season can reach 23,000 ppm [9, 17, 19], disrupting water treatment and meaning that only 50% of the population has access to safe drinking water. In some Sudanese rural areas, this can drop to 25% of the population in the dry season. Chemical treatment of water is often used and can create its own health impacts on the population. Turbidity may also result in eutrophication where nutrient-rich sediments are present particularly sediments from agricultural land with high fertilizer contents. Eutrophication creates a situation of oxygen depletion in the river water and its canal, and it may reduce to the point where fish species may be unable to survive. Eutrophication, where it results from toxic algal blooms, can also be a serious risk to human health. One of the benefits of AHD is that it helps the drinking water companies to improve drinking water quality in Egypt due to trapping the sedimentation in the front of the AHD lake especially in the Sudan part.

5 Conclusion and Recommendation

Egypt is a country suffering from deep water shortage exceeding 42 BCM/year in addition to its dry and high-temperature weather. The agriculture sector consumes 85% of their total water resources and about 103% of its Nile share water. Nile water discharge is not stable and differs from year to year and from high flood years to a severe drought in another year. The Nile River wastes about 22 BCM/year in the Mediterranean Sea; thus Egypt planned to construct a great dam to store the water in the high flood year, to keep the Nile water from being wasted in the sea, and also to use this reservoir in the drought years. The impacts of both climate change and the building of mega dams in upstream countries especially in Ethiopia which is the main source of the Nile water providing 85% of its total water discharge will have great effects on Egypt. Accordingly, Egypt obliged to extend in reusing of agricultural drainage water, treated industrial and sanitation wastewater, as well as desalination of sea water. Egypt also should increase the efficiency of water delivery system through its open canals to be cemented in some of them and change some other to a close piping system. Egypt also should increase water use efficiency in the agricultural fields to change the irrigation methods from flooding to scarce modern methods such as surface and subsurface drip, sprinkler, and pivot irrigation. Rationalization of water use is the only way for Egypt to dealing with the future.

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Impacts of Constructing the Grand Ethiopian Renaissance Dam on the Nile River

Mohamed Helmy Elsanabary and Abdelkader T. Ahmed

Contents

Abstract The Nile River (NR) is the primary water resource and the life artery for its downstream countries such as Egypt and Sudan. This chapter focuses on the impacts of constructing the Grand Ethiopian Renaissance Dam (GERD) on three main parts of the NR: close to Sudan-Ethiopia border; near Khartoum, Sudan; and the main Nile at the entrance of Lake Nasser, Egypt. The dam is designed to create a storage reservoir that will maintain a holding capacity of about 74 billion cubic meters of water at the full supply level. The impacts are divided into two main categories which are hydrological and environmental impacts. By studying the hydrological impacts, the study delineated the

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reservoir area to estimate the reservoir volume and its geometrical dimensions for all possible scenarios from starting the dam construction up to reaching the full operation and storage capacity. Results show that the best-accepted scenario for constructing the dam is by filling the dam reservoir with 10 BCM/year or less in 3.8 years. Furthermore, the impacts of the dam breach on Ethiopia and the downstream countries are studied via simulations from HEC-RAS model. In case of dam breach, a severe flood will result in inundation of the Sennar Dam, Sudan, 15 km wide and 200 km long, and the areas in between, until it reaches Khartoum, Sudan. Also, excessive water level with 3 m rise is expected from the dam until it reaches Nasser Lake. By studying the environmental impacts, particularly those of the population displacement, carbon dioxide emissions, agricultural lands, animals, and aquatic life, we will gain a better understanding of potential risks. This chapter discusses successes and many drawbacks of the GERD construction and its hydrological and environmental impacts on the Nile River downstream countries.

Keywords Dam breach, Dam impacts, GERD, Nile River, Streamflow, Water management

1 Introduction

Due to the increasing water demand, the world has been facing a serious water crisis since the beginning of the twenty-first Century [1]. For example, the rise of living standards and population growth has put more stress on the earth's water resources. In the case of trans-boundary areas, rivers are one of the most important freshwater resources worldwide, and their water must be managed in a convenient way. This chapter discusses the impacts of constructing the Grand Ethiopian Renaissance Dam (GERD), which is expected to be operational on the Blue Nile (BN) River in Ethiopia in early 2018. Like many large-scale dams on trans-boundary rivers, GERD has been criticized for potentially compromising downstream water security and livelihoods through upstream country decisions to construct such dams. Retaining and storing river water for various purposes, such as hydropower, flood control, and irrigation purposes, must be agreed upon and managed by all riparian countries sharing these rivers. Dam construction on rivers is a significant endeavor that imposes many impacts and should be studied by all affected riparian countries.

The Nile River (NR) is one of the trans-boundary rivers which faces these conflicts. The NR, which is shared by 11 riparian countries, is the life artery for water demands particularly the downstream countries, i.e., Egypt and Sudan. The NR runs through very different climatic regions. Due to climate change and variability, the amount of water in the Nile Basin may fluctuate and water availability is vulnerable. The NR Basin is characterized by water scarcity, population growth, and poverty that will likely cause the future to be very uncertain. Development projects in the basin countries including irrigation, hydropower dam, and other water diversion projects may cause conflicts between the riparian countries [2]. Constructing water control structures on the NR basin will affect the riparian countries especially the downstream countries.

The NR streamflow that Egypt relies on comes from two sources. The first, and most important, is the Ethiopian Plateau where the Upper Blue Nile Basin (UBNB) is located. Typically, during July to October, about 80–85% of the NR total streamflow at Aswan, Egypt, comes from the BN (Abay) River [3, 4]. The second source that compensates the rest of the year is the Great Lakes region of Africa, which provides about 15% of Egypt's needs.

In the early twentieth century, engineering proposals for the regulation of Lake Tana, at the headwaters of the Blue Nile, were investigated [5], and several subsequent studies have focused on the feasibility of regulating its outflow. These proposals suggested two possible reservoir sites along the BN; however, there were some difficulties due to the fact that the BN flows through deep valleys. Hurst et al. [6] suggested constructing high dams on the BN with small capacities. Garstin [5] highlighted a concern about the huge volumes of sediment carried by the BN. The US Bureau of Reclamation [7] prepared a detailed study of the Blue Nile region, including its hydrology, water quality, geology, physiography, mineral resources, sedimentation, land use, groundwater, and local economy. In addition, some irrigation and hydroelectric projects were recommended. The US Bureau of Reclamation [7] concluded that there are approximately no lands along the BN which can be irrigated between Lake Tana and the Sudanese-Ethiopian borders. Four dams for the hydroelectric projects were proposed for the BN downstream of Lake Tana, namely, Karadobi, Mabil, Mendaia, and the Border Project.

The Border Project GERD is a hydropower project being built on the BN to generate 6,000 MWh of electricity and estimated production of 15,000 GWh per year by exploiting the river's streamflow which has an average of 1,541 m^3/s of annual water discharge. The dam is a roller compacted and reinforced structures 1,780 m long and 155 m high [8]. It has two power stations installed at the foot of the dam. The dam is designed to create a reservoir that has a holding capacity of about 74 billion cubic meters (BCM) of water at the full supply level. The idea of constructing the GERD arose after 2009 [9–11]. Few studies have highlighted the impacts of constructing GERD. For example, Chen and Swain [12] evaluate strategic priorities, sustainability standards according to the World Commission on Dams (WCD) framework, and geopolitical significance, concluding that project planning has largely ignored the WCD's guidelines and offered limited transparency. Gebreluel [13] mentioned that constructing such a dam would provide Ethiopia the capacity to disturb the water flows of the world's largest river in a significant manner. Taye et al. [14] concluded that the region is encouraged to share data and information with respect to hydro-solidarity principles, which encourages equitable and reasonable utilization of international watercourses. Mohamed and Elmahdy [15] showed that the major faults crosscut the northern and southwestern hills and are parallel with the faults that crosscut the GERD site, and their displacement directions are perpendicular to the GERD walls, creating alarm. Furthermore, studies on the hydrological, environmental, and social impact of the dam on the area and the communities are mandatory.

This chapter studies the hydrological and environmental impacts of constructing the GERD, close to the border of Sudan on the BN River, to evaluate the impacts of such project on the countries downstream the dam, i.e., Sudan and Egypt. This study aims to identify, predict, and analyze the impacts of the GERD on the NR streamflow, the possibility of the dam breach, and the environmental impacts that are likely to arise from the project stages and their effects on the downstream countries, Sudan and Egypt.

2 Study Area

There are three study areas. The first study area is located in the Upper Blue Nile Basin (UBNB) which is 176,000 km^2 in area with a mean annual streamflow volume of 48.5 BCM, i.e., approximately 1,541 m^3/s, and occupies 17% of Ethiopia. The Blue Nile begins at Tana Lake of an approximate elevation of 1,800 above mean sea level (amsl), and the water leaves the lake via dropping over 50 m [16]. The UBNB, which forms the western part of the Ethiopian Highlands, receives annual precipitation of 1,600 mm with a range of ±600–800 mm/year [17] more than the eastern, northern, and southern parts of the Ethiopian Highlands. The precipitation variability is expected since the western part is higher than other parts of the Highlands, and precipitation generally increases with altitude because of orographic effects [18]. The GERD is located on the BN River, 5 km away from the Ethiopian-Sudanese borders as shown in Fig. 1. The proposed dam is located in the Ethiopian Highlands in a region characterized by elevated plateaus in a mountainous area. GERD is a gravity dam and will be 155 m in height and 1,780 m long. It will be constructed in the same location where the Border Dam was proposed but with significant changes in the specifications of the dam. The second study area is located between the GERD and Khartoum, Sudan, while the third study area is the area from Khartoum to the entrance of Lake Nasser, Egypt, as shown in Fig. 1.

3 Models

In order to investigate the hydrological impacts of the GERD, the study utilized two main models which are: first, the ArcInfo version 10.1 software which is used for delineating and determining the surface area of the dam storage reservoir and, second, HEC-RAS (River Analysis System) model as a 1-D streamflow model. HEC-RAS is part of the family of public domain generalized simulation models and available from the Hydrologic Engineering Center (HEC) which was developed by the US Army Corps of Engineers, USA, in 1998 [19]. HEC-RAS is an integrated system of software for interactive use in a multitasking environment. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphical and tabular output, and reporting facilities. The model is used to simulate the impact of the GERD failure, with low and high releases on the Sudanese lands downstream of the dam. The model is designed for calculating water surface profiles for steady and gradually varied flow. The steady flow approach is capable of handling a full network of channels or a single river reach.

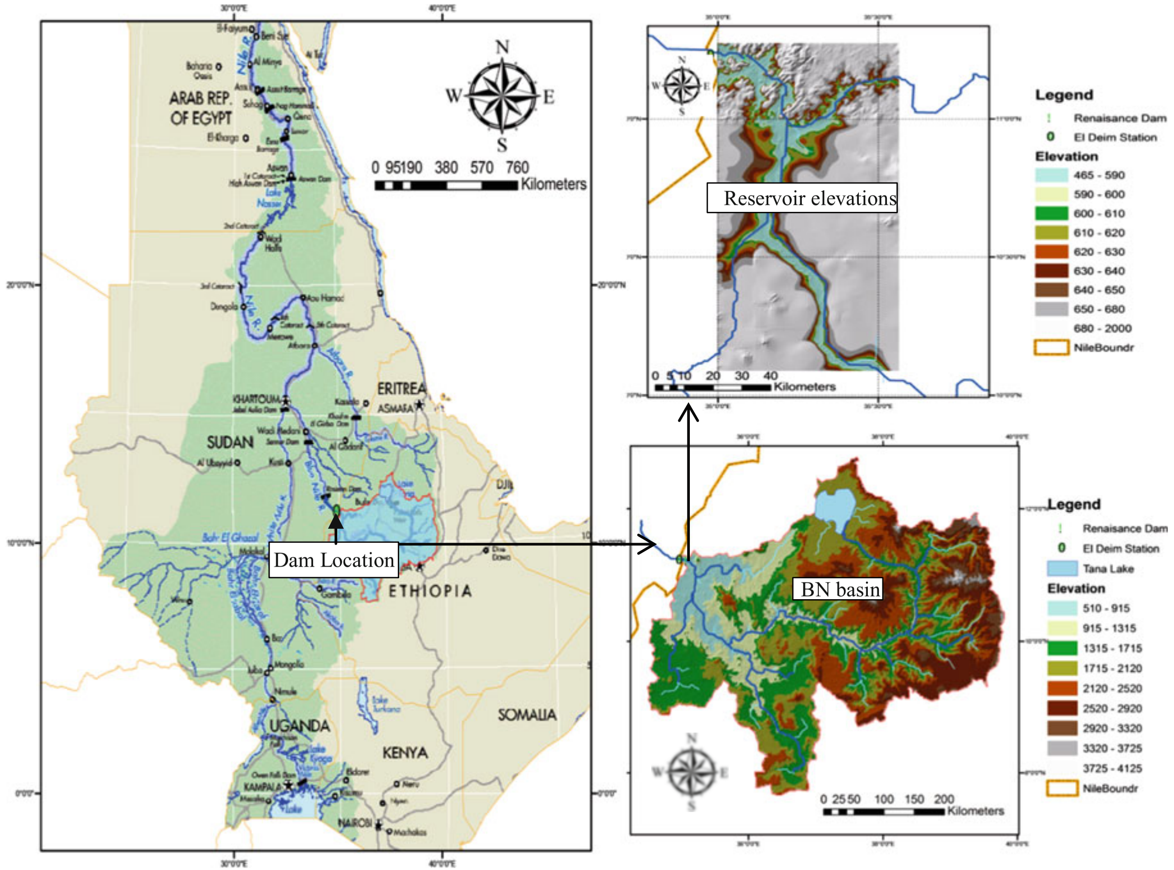

Fig. 1 Maps for the study area and the dam location. The Nile Basin map was adopted from the World Bank

HEC-RAS computational procedure is based on the solution of the one-dimensional energy equation.

3.1 ArcGIS Data

The data required for driving the ArcGIS software are topographic, land use, and hydrometric data. The DEM dataset of UBNB was extracted from the Global 30 Arc-second (1 km) Elevation Data Set (GTOPO30), a global raster Digital Elevation Model (DEM) with a horizontal grid resolution of 30 arc s (approximately 1 km). The data is expressed in latitude and longitude and is referenced to the World Geodetic Survey (WGS) system of 1984. The DEM data were used to determine the reservoir surface area and volume, drainage area, drainage network, and flow direction of the rivers and streams of the UBNB. For the UBNB terrain analysis that does not require high accuracy, the basic delineation procedure used in this study should be sufficient. However, for determining the drainage network, this could cause some problems.

3.2 HEC-RAS Data

The HEC-RAS model input data includes geometric and hydrologic data. Cross sections are one of the main inputs to the model. DEM data are used to extract the elevation data from the terrain to create a ground profile across channel flow. The cross sections are used to compute HEC-RAS attributes such as bank stations (locations that separate the main channel from the floodplain), downstream reach lengths (distance between cross sections) and Manning's (n). Therefore, creating an adequate number of cross sections to produce a good representation of channel bed and floodplain is critical. The geometric data is composed of about 30 cross sections with a spacing of 40 km in between extracted from the DEM data. The inflow boundary was defined as the inflow discharge downstream the GERD (276 mm/year) at all the main junctions along the Nile River. Manning's coefficient ranges from 0.05 to 0.1 as described in [20]. The Manning values were estimated according to the normal wet season flow. Chow [21] concluded that the roughness coefficient decreases with the increase in water level. The study focused on the steady-state simulation. Therefore, all the simulations considered the filling during the average flow years between the flood and drought seasons to address the total effect of the proposed dam on the downstream countries.

4 Results and Discussions

4.1 Hydrological Impacts Assessment of the Dam

4.1.1 Dam Storage Reservoir

The GERD was planned initially to create a lake that would store 14 BCM of water; however, the lake's capacity increased to 74 BCM. According to Ethiopian officials [11], this volume should cover a surface area of 1,680 km^2 with a maximum water head of 145 m behind the proposed dam. In this study, the reservoir surface area and volume were calculated via ArcGIS software software based on different stored water level scenarios. These scenarios included storing water at different elevations behind the dam beginning from elevation 590 m, i.e., 96 m head behind the dam, and by increasing 10 m in each scenario up to 640 m level which gives water head of 146 m. According to the elevations of the ground in the study area, the model results showed different suggestions for the water area and volume of the reservoir as shown in Fig. 2. Results showed that there is no correlation between the values declared about the dam reservoir. As at level of 640, i.e., 146 m head behind the dam, the reservoir has 1,561 km^2 and a volume of water equal to 79 BCM. Results show also that the volume of 74 BCM needs only 1,426 km^2 and 136 m water head. Moreover, reservoir authorities have declared that the storage area will be 1,680 km^2 [11]; according to the analysis, the storage capacity corresponding to the storage area will be 84 BCM. In a visual comparison to the different cases generated by the model as shown in Fig. 3. Figure 4 shows that the declared proposed reservoir is greater than the shape of the biggest storage volume of 79 BCM. This refers to either the shortage in data collection for this project or might be the intention to hide such values to reduce the downstream countries from the fear of constructing the dam. In hydroelectric dams, the storage reservoirs are usually less than 14 BCM in capacity. This increase in size contradicts with the declared goal of building the dam to supply the country with hydroelectric power. Storing water at level 600 which is corresponding

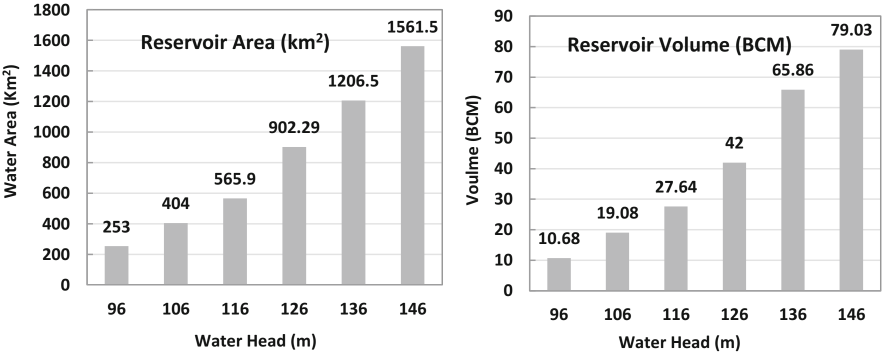

Fig. 2 Reservoir water area and reservoir volume at different water heads behind the dam

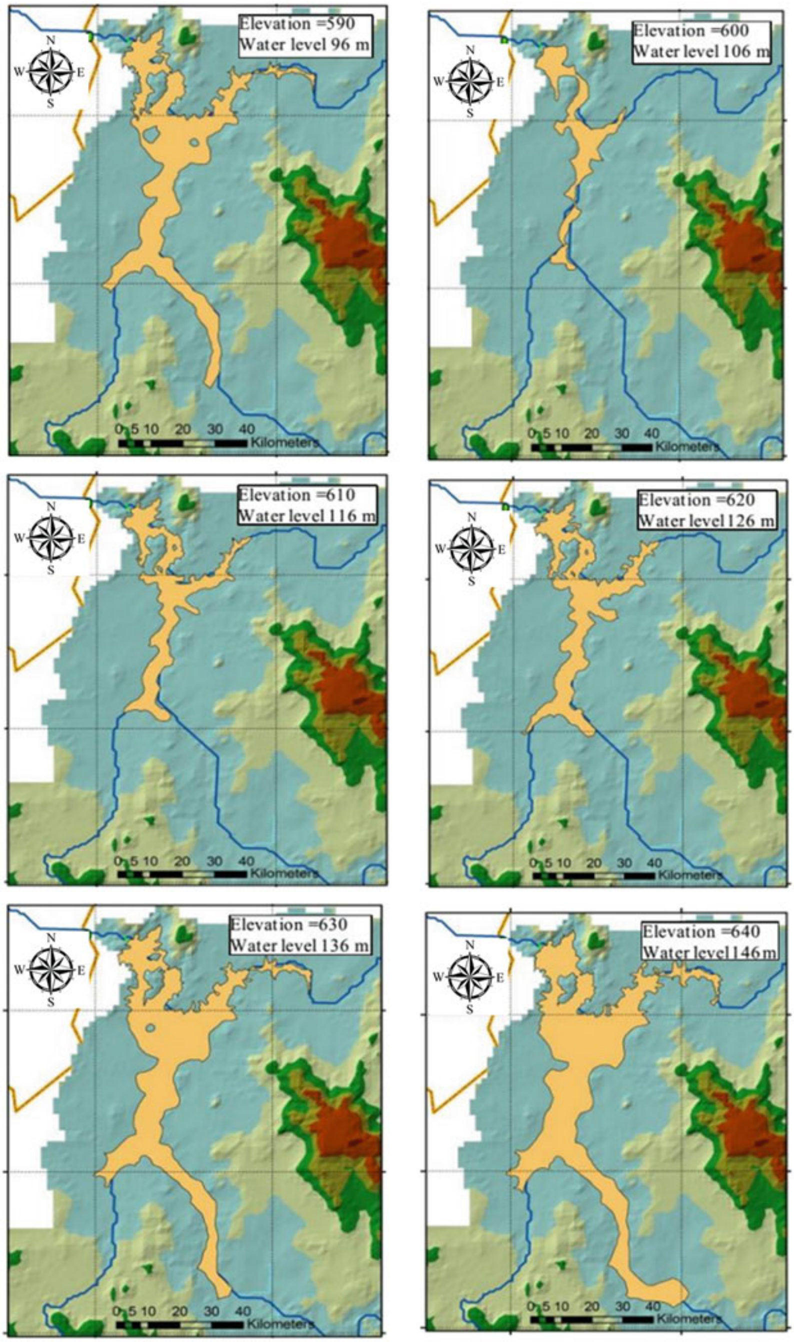

Fig. 3 Reservoir water area at different filling water levels (head)

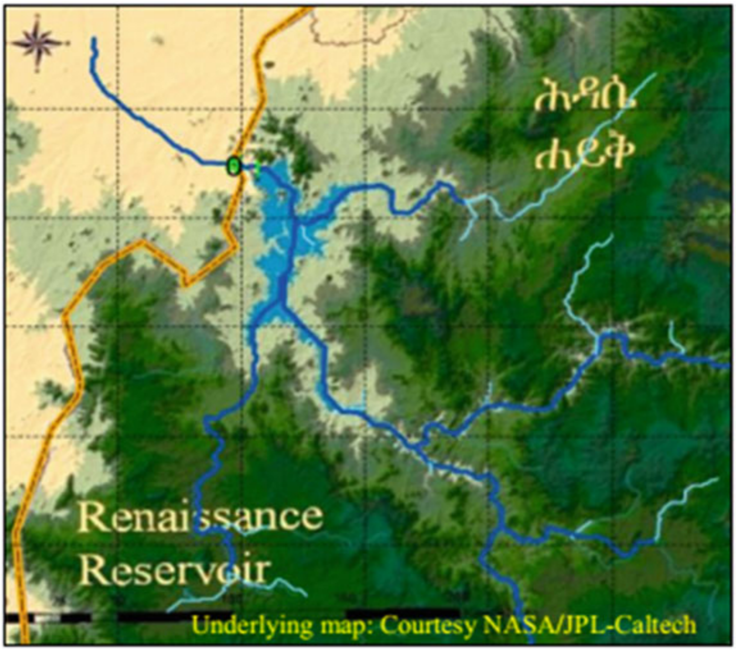

Fig. 4 Proposed impounded storage reservoir behind the Renaissance Dam (published by the Ethiopian Authority)

to 106 m water head behind the dam and 19 BCM volume of water will be the suitable and sufficient scenario for generating electric power.

4.1.2 Reservoir Filling Scenarios

One of the key points to the water managers within the Nile River Basin is the filling stage of the GERD reservoir. To date, no reservoir filling rate policy has been established for the GERD or even announced. This policy will have clear implications on the GERD's ability to generate hydropower in the near-term and the impacted people and livelihoods in the downstream countries of Sudan and Egypt through reduced streamflow. Four scenarios of reservoir filling rates 2, 5, 10, and 20 BCM/year were adopted to estimate the sufficient period to fill the reservoir for the six water level scenarios (96, 106, 116, 126, 136, and 146 m) that were discussed in the above section. Results showed that the time periods needed to fill the reservoir at 146 m of water level behind the dam were 39.5, 15.8, 7.9, and 3.95 years for the four-time scenarios, respectively, as shown in Fig. 5. For the case of 74 BCM with a water level of 146 m, times needed were 37, 14.8, 7.4, and 3.7 BCM/year, respectively. These results show a significant problem coming with charging the reservoir even at a longer filling period such as 40 years.

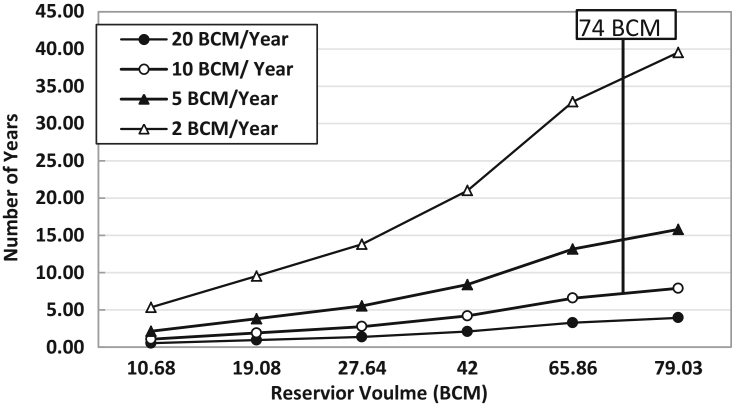

Fig. 5 Reservoir volume at different filling rate sceneries for the 79 BCM reservoir capacity. Adopted from [22, 23]

The effects of filling period of the reservoir on the Egyptian water demand were studied. The results showed that severe water shortage problems will affect Egypt even with using the storage water in Nasser Lake which may help to compensate the water shortage problem for 70% of the filling periods in most of these scenarios as shown in Fig. 6. Based on the results discussed herein, the best-accepted scenario for constructing the dam is by filling its reservoir with the initial plan of 19 BCM only or less in around 3.8 years by using the filing rate of 5 BCM/year. This amount of water will be sufficient for power generation and have less impact on the downstream counties, i.e., Egypt and Sudan.

4.1.3 Dam Failure Scenarios

Dams are very important for hydroelectric production and flood control by the means of water storage. Also, the reservoirs retained upstream these dams provide water for human and agricultural consumption. However, dams can also cause serious risk for the downstream river basin, agricultural land, historical sites, wildlife habitat, and communities in the catastrophic event. A catastrophic event such as dam failure or breach, caused by geological/foundation weakness (e.g., earthquakes), dam overtop due to extreme storms, structural problems, old age, terrorism or military attacks, etc., is of great concern to the dam downstream country officials in terms of community preparedness and response.

The outflow boundary condition was used as the water level at the end of the BN River, near Khartoum. The simulated runs were performed to forecast the effect of dam failure on the water profile of the BN River. The average longitudinal slope of the BN River is about 10.77%. The approximate average velocity is between 1.22 and 2.13 m/s [24]. Due to GERD construction, the hydrological and physical properties of the BN River downstream the dam will change. Furthermore, the water quantity

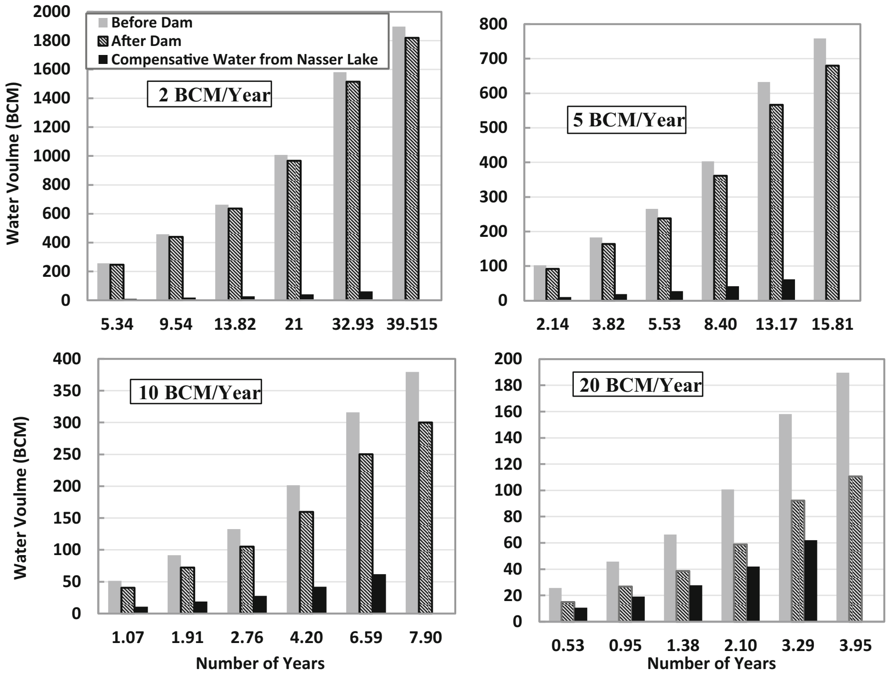

Fig. 6 Effects of filling period sceneries of the reservoir on Egyptian water demand

discharged from the river and the flow velocity after the dam will be reduced. In this study, several scenarios of water charging in the reservoir were studied via the model to check their impacts on the streamflow downstream the dam.

A failure impact assessment must be prepared to evaluate the population at risk if a failure of the water dam was to occur. A dam is considered to have failed if there is a physical collapse of all or part of the dam or an uncontrolled release of any of its contents.

The main purpose of studying these scenarios is to simulate the expected flood due to the failure of the proposed GERD and its impacts on Khartoum, Sudan, and the main Nile at the entrance of Lake Nasser, Egypt. A one-dimensional steady flow mathematical model was used to achieve this purpose. The proposed model is called HEC-RAS, which has been developed for the US Army Corps of Engineers by the Hydrologic Engineering Center, to predict the possible impacts of different low and high releases. Different releases were simulated (e.g., 1,541, 1,478, 1,383, 1,224, 907, and 2,506 m^3/s) which represent the original streamflow before constructing the dam. The releases represent the streamflow which is reduced by 2, 5, 10, and 20 BCM and sudden failure of the dam, respectively, to evaluate the impacts of inundation process as shown in Table 1.

Table 1 Input streamflow for different reaches on the Nile River

	Discharge (m^3/s)					
River reach	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
El Diem to Khartoum	1,541	1,478	1,383	1,224	907	2,506
Khartoum to Atbara	2,456	2,386	2,282	2,107	1,759	3,518
Atbara to Nasser Lake	2,837	2,767	2,662	2,488	2,139	3,898

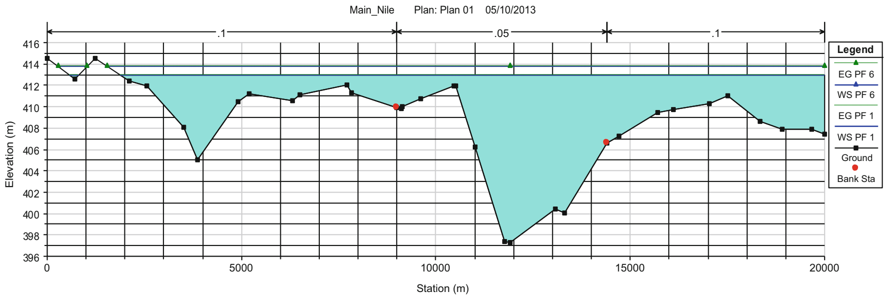

Fig. 7 Water profile after dam failure due to the release of stored water. Adopted from [22, 23]

The original streamflow is assumed based on the historical average annual discharge of 48 BCM coming from the Blue Nile. After crossing the Sudan border, the Blue Nile flows for a distance of about 7,000 km until it meets with the White Nile at Khartoum. The White Nile adds 24 BCM/year until it reaches Khartoum, while Atbara River provides 12 BCM/year to the main NR streamflow. Each release affecting the land and infrastructure inundations was analyzed and evaluated. The planned releases may have impacts on the downstream countries of the dam. Many problems for human properties and activities especially in the area of encroachment are evident specifically under the dam damage or even failure. By taking a cross section in the Blue Nile near Sennar, the simulation result shows a water surface rise by about 2–3 m as shown in Fig. 7. After the failure of the dam, the cross section experiences excessive flood with the high water level. Also, results showed that the flooded area covers the extension of 15 km width for 200 km long around Sennar and extends 210 km from Sennar to Khartoum.

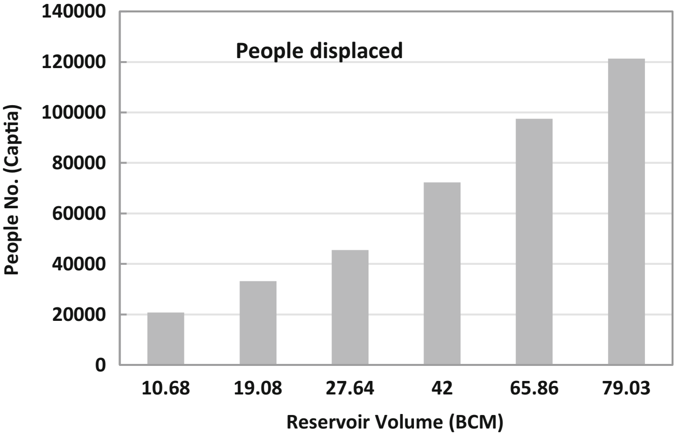

Fig. 8 Environmental impact of the GERD on the people relocation. Adopted from [22, 23]

4.2 Environmental Impacts of the Dam

4.2.1 Impacts of Dam Reservoir on the Host Country

People Resettlement

The worst adverse impact associated with the large dams is people resettlement. Thus, the most important negative effect of constructing the reservoir, upstream the GERD, on the host country, Ethiopia, is the displacement of people living in the area of the proposed reservoir. The population of 20,000–122,000 capita will be relocated due to the different scenarios of reservoir volumes mentioned above. The results of people relocation are shown in Fig. 8. Furthermore, Tortajada et al. [25] reported that living standards could be expected to drop leaving people worse off than would have been the case before constructing the dam and in comparison to their neighbors whose resettlement is not required.

The living standards for the majority of people can be expected to drop due to many reasons. For example, infrastructures, new schools, and other social services or upgrade development staffing are even less likely to be built. Another reason of removal adversely affecting living standards is caused by the reduction of cultural inventory that accompanies involuntary resettlement. Sociocultural stress can have many manifestations due to the departure from a preferred homeland and difficulties associated with resettlement areas.

Greenhouse Gas Emissions

The natural lakes and wetlands, as known, have an active exchange of gases with the atmosphere. Ruttner [26] reported that the process of degradation of organic material

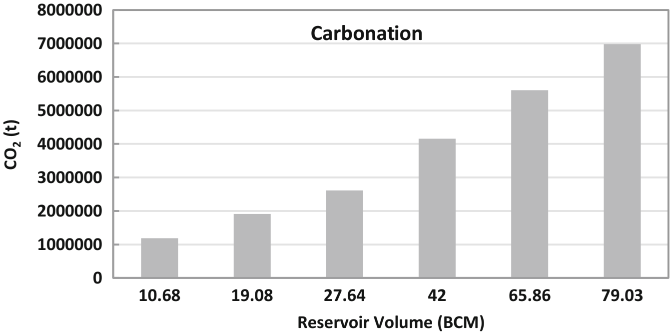

Fig. 9 Environmental impact of the GERD on the carbonation at different scenarios of reservoir volumes. Adopted from [22, 23]

consumes O_2 and releases CO_2. The sediment is important in this process, acting on one hand as a sink of carbon since sediment material is often rich in organic carbon, while on the other hand, the degradation processes release carbon from the sediment. In the GERD case, Tropical Shrub is the common plantation in the site of the proposed reservoir. The initial filling of the reservoir floods the existing plant material, leading to the death and decomposition of these plants. The decaying plant matter settles to the non-oxygenated bottom of the reservoir and decomposes and eventually releases dissolved methane. The amounts of carbonation for each scenario of reservoir volumes ranged between one and eight million tons of carbon dioxide emission as shown in Fig. 9.

Furthermore, the dam also will affect aquatic habitats such as fish because they inhibit fish migration in a river. Some fish species have been able to spawn and grow to substantial size. Due to the high water level expected between 96 and 146 m as in the different scenarios shown previously in Fig. 2, many fish that try to swim up or down the river become disoriented by the warm water and slower current of the reservoir. Some fish that try to pass directly through the dam's turbines are killed. The upriver spawning migrations of seven endemic *Labeobarbus* species of Lake Tana are also affected by the development activities such as small-scale irrigation and dam construction at the inflowing rivers [27].

4.2.2 Impacts of Dam Reservoir on the Downstream Countries

The Blue Nile River transformation downstream of the GERD from a free-flowing river ecosystem to an artificial water canal habitat is considered the major impact which commonly happens after the construction and operation of GERD. According to the HEC-RAC model results in the different four-time scenarios for filling the reservoir discussed above, water velocity will be reduced by 5, 11, 20, and 42%, respectively. Furthermore, the water temperature in the river will be colder than it should be, and this reduction can be estimated according to [28] by 0.5–1.5°C. These changes in temperature and other water characteristics such as chemical composition, dissolved oxygen levels, and the physical properties of the water are often not suitable for the aquatic plants and animals that evolved with a given river system. The dam also holds back sediments that would naturally replenish downstream ecosystems. The agricultural lands and scattering millions of families will be affected due to the reduction in the water share of downstream countries especially Egypt. Results presented previously in Fig. 5 showed different scenarios of charging the reservoir and the sever water demand in Egypt. It would also result in increasing the pollution of the water streams and creating problems in the supply of water for drinking and industry. There will also be problems in river transportation, Nile tourism, and threats to the fish farms. When a river is deprived of its sediment load, it seeks to recapture it by eroding the upstream riverbed and banks which can undermine bridges, dams, and other riverbank structures.

From the flood inundation areas resulting from the GERD failure scenario, the area surrounding the Sennar Dam will be flooded and considered as a major threat to that dam. Therefore, such scenario will lead to flooding the most fertile lands in Sudan which is the homeland to the large population there.

4.3 Post-construction Assessment of the Dam

The net impacts of the large dams can be determined authoritatively and comprehensively if there is an answer for the simple question of the real expenses and benefits of the large dams. The debate on dams needs to be resolved conclusively for the last time, so that appropriate water development policies can be formulated and implemented, especially in the developing countries, which will increase their overall social and economic welfare. One of the most important reasons why the recent argument on dams has increased is the absence of aims and detailed ex post analyses of the economic, social, and environmental impacts of large dams [25]. Accordingly, the impacts and benefits of the GERD need to be studied more deeply by the host and downstream countries to decide the appropriate size and operation of this dam. One of such studies by Mulat and Moges [29] highlighted that there will be about 12% and 7% of reduction of annual energy output from the High Aswan Dam during the filling and after filling stages of GERD, respectively.

4.4 Policy Implications

The development of water resources of the UBNB in Ethiopia is very important to the country and the downstream countries (i.e., Sudan and Egypt). However, the implications of the likely long-term development of the Blue Nile resources in Ethiopia on Egypt and Sudan must be studied carefully. In the middle of the twentieth century, the US Bureau of Reclamation USBR in 1964 prepared a detailed study of the Blue Nile region, and hence some hydroelectric projects were recommended [7]. The Bureau suggested four dams to be established on the Blue Nile downstream of Lake Tana, namely, Karadobi, Mabil, Mendaia, and the Border Project. Together these four dams would have an initial active storage capacity of about 51 BCM annually and an estimated electricity generation of over 2,900 MWh, about three times the actual production of the Aswan High Dam [30].

The Border Project is one of the four suggested dams by the USBR which is known recently as GERD and discussed herein. It was planned in the past by the US Bureau of Reclamation [7] to store 11 BCM and generate electricity of 1,400 MWh. Recently, the plan was changed to store 74 BCM. This major change in the original plan refers the misuse of the water resources of Blue Nile and has significant effects on the allowance of Egypt and Sudan from Blue Nile water. In addition, as discussed earlier, using such huge reservoir and dam without peer studies has the potential of the collapse and increases the negative environmental impacts of the project on its area and neighbors. Biswas [31] stated that the main reason why the current non-productive argument on dams has succeeded is that of the absence of objective and long-run in-depth ex post analyses of the physical, economic, social, and environmental impacts of large dams after their construction. Biswas and Tortajada [32] reported also that various alternatives may be selected for the construction of properly planned and designed dams, which could be large, medium or small. It should be realized that in the real world of water resources management, small may not always be beautiful and big could be sometimes a disaster. Each alternative should be judged on its own value and within the context in which it is to be applied. The solutions selected must not be rigid and should always reflect the needs of the areas with consideration the needs of neighbors.

5 Conclusions

The Nile River (NR) is the primary water resource and the life artery for its downstream countries such as Egypt and Sudan. This chapter focused on the impacts of constructing the Grand Ethiopian Renaissance Dam (GERD) on three main parts of the NR: close to Sudan-Ethiopia border: near Khartoum, Sudan; and the main Nile at the entrance of Lake Nasser, Egypt. This chapter investigated the hydrological and environmental impacts of constructing the GERD. The chapter showed the following results:

- There is no correlation between the GERD technical specifications declared by the Ethiopian authorities about the dam reservoir. As at a level of 640, i.e., 146 m height behind the dam, the reservoir has 1,561 km^2 and a storage volume of water equal to 79 BCM (or even more). The conflict between the storage volumes is due to either the shortage in data collected for this project or to avoid any political conflicts by reducing the fears from the downstream countries, i.e., Egypt and Sudan.

- The filling of the dam reservoir causes water shortage to the downstream countries even for a longer period of time.
- In the case of dam breach, a severe flood will result in inundation of the Sennar Dam, 15 km wide and 200 km long, and the areas in between until it reaches Khartoum City in Sudan. Also, excessive 3 m rise in water level is expected from the breached dam until it reaches Nasser Lake in Egypt.
- With the massive volume of the storage reservoir at a capacity of 79 BCM, 122,000 people will be displaced in addition to the CO_2 emissions which are estimated at 7 million tons.
- The reduction in the water share of downstream countries especially in Egypt and Sudan will impact the agricultural lands and relocation of millions of families.
- River water velocity will be reduced between 5 and 42% and the temperature reduced by 1.5°C. These reductions will cause changes in the physical properties along with other alerted characteristics of the water which is often not suitable for the aquatic plants and animals that evolved with a given river system.
- The GERD construction causes the misuse of the Nile River water resources and has significant hydrological and environmental impacts on the allowance of Egypt and Sudan from the Blue Nile water.

6 Recommendations

- The best-accepted scenario for constructing the dam is by filling the reservoir with 5 BCM/year or less in minimum 3.8 years with a total storage volume capacity of 19 BCM. This amount of water will be sufficient for hydroelectric power generation and causes less impact on the downstream countries.
- The water reserve, from Nasser Lake, may help to overcome the reservoir filling period for around 70% of the filling periods in most of all scenarios. However, that may cause ecosystem problems in the lake due to the reduction of its water reserve.
- The proposed solutions must not be rigid and should always reflect the needs of the human activities taking into consideration the demands of the riparian countries.
- It is important that the Ethiopian authority prepares an emergency action plan for the GERD breach scenarios.

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Stochastic Investigation of the GERD-AHD Interaction Through First Impoundment and Beyond

Khaled H. Hamed

Contents

Abstract The Grand Ethiopian Renaissance Dam (GERD) is currently being constructed on the Blue Nile. In the short term, water inflow to the Aswan High Dam (AHD) reservoir will be reduced as water is abstracted during GERD's first impoundment. In the long-term, the inflow to AHD will be affected due to flow regulation and additional evaporation losses from GERD. This chapter presents a stochastic analysis of the impacts of GERD on AHD. Synthetic Nile flow series that preserve the Hurst exponent of the flow are generated using a Fractional Gaussian Noise (FGN) model. Results from the simulation of 1,000 equally probable Nile flow series using a simplified GERD-AHD system model are analyzed. The results indicate a very high downstream risk when GERD is operated as an annual storage reservoir, which questions the economic attractiveness of GERD in a regional context when operated solely for hydropower energy maximization. Operating GERD as a long-term storage reservoir results in reduced, yet still considerable

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impacts. Optimal GERD filling and operation policies aimed at minimizing downstream risks through a comprehensive regional economic, environmental, and social analysis are urgently needed.

Keywords Aswan high dam, Extended drought, Grand Ethiopian Renaissance Dam, Hurst phenomenon, Impact assessment, Stochastic simulation, Water deficiency

1 Introduction

Several studies in the literature have addressed the impact of the Grand Ethiopian Renaissance Dam (GERD) on the downstream countries, and particularly on the water availability for Egypt and Sudan as well as hydropower generation from the Aswan High Dam (AHD) and Old Aswan Dam (OAD) hydropower complex. However, most of these studies do not fully consider two important interrelated aspects of future Nile flows. The first aspect is the condition of the Nile flow during GERD first impoundment and beyond, while the second aspect relates to the proper representation of the natural variability in the Nile flow sequence.

Regarding the first aspect, the problem is related to the following question: What will be the flow conditions during and shortly after GERD first impoundment? In assessing the downstream impacts, usually, a simulation model is used, with the input being inflow time series at key source points in the Nile system. Many studies simply use the historical time series as is, starting somewhere in the 1900s with above-average flows, with the well-known extended drought period (1980–1989) occurring much later than the critical period of GERD initial filling. Using such a time series would result in minimal impacts on the downstream. However, due to the stochastic nature of river flows, the repetition of the historical time series with the same sequence is practically impossible. Drought periods similar to, or even more severe than the recorded 1980s drought, may occur at any point in time in the future. In fact, given the length of time that elapsed since the last recorded drought period, the Nile may be overdue for a similar, if not more severe drought. To account for such possibility, some studies use a number of subseries at different starting points to perform the assessment (e.g., high flow subsequence, average flow subsequence, and low flow subsequence). The impacts, in this case, become conditional on the subseries used. This method only captures a limited part of the variability of flow and in turn a limited part of the variability in the impacts, which does not allow accurate assessment of the likelihood of different critical impacts.

The second aspect is related to the mathematical description of the underlying natural stochastic process generating the Nile flows. Some studies overcome the shortcomings of using the historical record by generating synthetic flows using several stochastic models. However, a very important feature of the Nile flow that is central to reservoir storage theory has not been considered in previous studies. This feature is widely known as the “Hurst Phenomenon,” named after Harold Edwin

Hurst [1] based on his extensive studies of the Nile flow as well as several other natural time series. Natural time series that exhibit the Hurst phenomenon, also known as long-term persistence, are characterized by the occurrence of clusters of successive high values and others of successive low values. The most important implication of the Hurst phenomenon is that the cumulative interannual variability of the flow is much larger than what is characteristic of commonly used models of short-term persistence, such as the autoregressive (AR) or autoregressive/moving-average (ARMA) models. For the Nile river, Hurst [1] shows that storage requirements to overcome the maximum n-year deficit are proportional to n^h as opposed to $n^{0.5}$ in the short-term persistence case, where the exponent $h = 0.72$ is widely known as the Hurst exponent. According to this relationship, the Nile storage required at Aswan for a typical 100-year design period is around 2.8 times that required for an equivalent short-term persistence river. Alternatively, a 100-year reservoir size based on short-term persistence would be sufficient only to overcome a 24-year maximum drought in a long-term persistent river. Obviously, using synthetic data generated by short-term persistence models greatly underestimates the impacts of GERD on the downstream.

In this chapter, a stochastic framework is applied to overcome the two shortcomings mentioned above of the current studies on the impacts of GERD on AHD water availability as well as hydropower generation. The methodology is aimed at deriving an approximation of the full probability distribution of the impacts using synthetically generated flow sequences that preserve the Hurst exponent of the historical data. A rather simplified approach is used in this study to assess the impacts under general conditions. A more advanced simulation model, probably with optimization capabilities, can be constructed to refine the results further as well as to suggest possible mitigation measures. In assessing the impacts of GERD on AHD, two key issues will be particularly highlighted. The first issue is the net change in system losses due to the introduction of GERD. The second issue is the effect of GERD operation concept on the downstream impacts.

2 Stochastic Simulation of GERD-AHD System

To assess the full probability distribution of the different impacts of GERD, a large number of simulations with equally probable inflow sequences are needed. These equally probable flow sequences are generated using a suitable method that ensures the preservation of the intrinsic stochastic properties of the historical flow sequence, including Hurst exponent. The resulting values of different impact indicators will also be equally probable and can thus be used to construct the full probability distribution of these indicators. The following subsections discuss the stochastic generation of synthetic flow data and the simplified flow simulation model used in this study.

2.1 Generation of Synthetic Flow Data

Several methods can be used to generate synthetic river flow data based on the stochastic properties of the historical record. These include classical autoregressive (AR) and autoregressive moving-average (ARMA) models, among others [2]. However, as mentioned earlier, these models do not preserve long-term persistence in the generated flow sequences as described by Hurst, which is essential to reflect the actual range of cumulative interannual variability in the Nile flow. Other models that have been suggested in the literature to preserve the Hurst phenomenon include Fractional Gaussian Noise (FGN) and autoregressive fractionally-integrated moving-average (FARIMA) models [3]. For the current study, we use an FGN data generator [4] to preserve the Hurst coefficient of the Nile flow data as well as its other important statistical properties.

In his original sizing of the Aswan High Dam (AHD), Hurst [5] has shown that the value of the Hurst exponent for the Nile flow is $h = 0.72$. Applying his empirical results to AHD storage requirements, Hurst estimated the design live storage as 90 km^3, which was deemed sufficient to guarantee a draft of 84 km^3 from the reservoir based on the expected range for a 100-year period. Hurst exponent values as high as $h = 0.85$ have been estimated in the literature [6], which would result in more storage requirements or, equivalently, more frequent reservoir emptying for a given reservoir volume. However, we will adhere to the original value $h = 0.72$ in this work.

For the stochastic data model, the historical Nile flow series were obtained from the records of the Nile Water Sector of the Ministry of Water Resources and Irrigation (personal communication) covering the period from 1911/1912 to 2010/2011. In the adopted stochastic model, the flow at AHD is numerically divided into two parts, flow coming from the Blue Nile through GERD, and the flow from all other sources (White Nile at Mogren, Rahad, Dinder, and Atbara at Khashm El-Girba). The analysis of the annual flow series indicates that the GERD inflow has mean $\mu_G = 48.90$ km^3 and standard deviation $\sigma_G = 8.73$ km^3. Sudan water uses including evaporation from Roseires, Sennar, and Merowe dams amount to 18.8 BCM [7]. Based on the data, the contribution of other sources after subtracting Sudan abstractions has been found to have $\mu_A = 22.84$ km^3 and $\sigma_A = 6.35$ km^3, with a correlation coefficient $\rho_{GA} = 0.72$ between the two series. Channel losses in the main Nile amount to some 3.74 km^3 on average [7], which represents about 5% of the average flow. To account for changes in losses with changes in flow, channel losses are thus taken as 5% of flow rather than a fixed amount.

It is to be noted that because of GERD regulation of the Blue Nile flow and interception of most sediment, Sudan dams on the Blue and the main Nile would, in general, be operated at higher levels throughout the year, since there would be no need for much regulation or sediment flushing [7]. This would result in an increase in evaporation losses between 0.5 to 1 km^3 depending on the new levels. Although these additional losses could further decrease inflow to AHD, they will not be considered in this study, assuming they will be considered as part of Sudan's share, which could reach around 20 km^3 inside Sudan (18.5 km^3 at Aswan).

A stochastic AHD inflow time series can be obtained by generating two correlated FGN series, one for the inflow to GERD and the other for the remaining sources, then regulating the GERD series through GERD reservoir, combining the resulting two series, and subtracting natural losses. Because all Sudan reservoirs are annual storage reservoirs, the generated annual series (based on a hydrologic year) is not affected by reservoir regulation. For the monthly series used in the simulation model, GERD annual inflow series is disaggregated based on the average Blue Nile flood hydrograph. For the combined GERD outflow with other sources to reach AHD, considering Sudan Dams offering little regulation after GERD construction, no further regulation is applied. At any rate, previous studies [7–9] indicate that due to the large overyear storage at AHD, the actual monthly pattern of the annual inflow to AHD has little effect on water availability downstream as opposed to interannual variability and water abstraction.

2.2 Flow Simulation Model

The flow simulation model consists of two components. The first component deals with flow regulation by GERD. The GERD reservoir maximum volume is taken as 74 km^3 at a maximum level of 640 m, with a maximum surface area of 1,904 km^2 [7]. Although some recent sources give a total volume of 79 km^3 (e.g., [10]), the more commonly mentioned reservoir volume of 74 km^3 will be used in this study. Naturally, a larger reservoir would involve more extreme impacts on AHD. The dead storage of the GERD reservoir is 14.8 km^3 at elevation 590 m. The annual rate of net evaporation losses at GERD is estimated at 1,078 mm/year [7]. This estimated value might need to be revised [11] since the losses at the nearby Roseires reservoir, whose lake ends at GERD, is estimated at 1,479 mm/year which is about 1.4 times that at GERD. Initial infiltration and deep percolation during the period of GERD first impoundment [11] are assumed to be 20% of the GERD storage volume. It is assumed that seepage and deep percolation losses will diminish with time to become insignificant, and thus will be neglected beyond the period of GERD initial impoundment.

In this study, in addition to the base case without GERD, two conceptual types of flow regulation by GERD will be considered for comparison. The first is annual regulation of the reservoir to maximize hydropower generation as announced by Ethiopia, which will be denoted here as “ETR.” In this study, full insight regarding annual flow will be assumed for this type of regulation, which represents an upper limit for hydropower generation. In practice, however, inflow forecasting would be required, which usually leads to relatively lower hydropower production due to forecast uncertainty. The second type involves operating GERD as a long-term storage reservoir that releases a constant annual flow equal to the long-term average of the GERD inflow minus expected evaporation losses from the reservoir, which will be denoted here as “LTR.” In the case of ETR, the reservoir is initially filled to 50 km^3 within 5 years, which enables reaching the full capacity by the 6th year of operation as announced by Ethiopia, after which the reservoir empties and fills annually, releasing the annual inflow. For the LTR case, filling of GERD beyond the dead storage of 14.8 km^3 (above the level 590 m) occurs only using excess flow above the long-term average, with the possibility of drawing GERD down to the dead storage level during low flow years to compensate the reduced inflow, which is the main function of a long-term storage reservoir.

The second component of the simulation model deals with flow regulation by AHD. The reservoir dead storage is around 31 km^3 at level 147 m. The full supply level is 175 m, where the live storage is 90 BCM, giving a total storage of around 121 km^3. At level 178 m, water is spilled through the Toshka spillway to the Toshka depression to the West of the reservoir lake. The maximum allowable level is 182.0, beyond which the emergency spillway of the AHD is activated. A wide range of estimates of the evaporation rate at AHD can be found in the literature [12]. The value of 2,701 mm/year used by NBI [7] will be adopted here for consistency, although a more reasonable average value of 2,450 mm/year is generally acceptable.

Operation of AHD is based on fixed monthly releases with a total annual demand of 55.5 km^3. In drought periods, however, a reduction of release is applied using a "sliding scale" as follows: reduction of 5% if AHD contents fall below 60 km^3, 10% if they fall below 55 km^3, and 15% if they fall below 50 km^3 [13]. This sliding scale is aimed at reducing the chances of reservoir emptying by spreading the deficit over a longer period, thus reducing the severity of water shortages, if any. No water can be abstracted from AHD below the dead storage level of 147.0 m. Furthermore, hydropower generation shutdown occurs at a level of 159.0 m (Ministry of Water Resources and Irrigation, personal communication).

3 Impact Assessment

The addition of GERD to the system will mainly result in the abstraction of part of the flow for the first impoundment, additional evaporation losses, and flow regulation; all of which will cause changes in the quantity and distribution of inflow to AHD. These changes in inflow will be reflected as changes in water release, water levels, evaporation losses, among other elements of the water balance, as well as changes in hydropower generation. The impacts will be studied at three different levels. The first level is the short-term impact through the first impoundment of GERD, which is assumed to occur within the first 6-years of operation. The second level is the medium-term impact for a 10-year period following GERD first impoundment, a period through which AHD would be most vulnerable to the impacts of GERD first impoundment. The third level is the long-term impact beyond the effect of the first impoundment. This period is chosen to be equal to 30 years and is assumed to start 70 years from GERD first impoundment to ensure that the impacts of the first impoundment have subsided and that the system has reached its new long-term equilibrium state. For all simulations, the initial level of

AHD will be set at 175.0 m, i.e., at full supply level. One could adopt a stochastically varying initial level for AHD, but the reservoir does seem to be currently full or near full, and GERD filling is expected to start soon.

Several indicators will be considered in assessing the impacts of GERD on AHD. The indicators are represented by their statistics over each period of analysis. These indicators are as follows:

1. The total deficit in AHD downstream release over the period of analysis (km^3)
2. The maximum deficit in AHD release in 1 year (km^3)
3. Number of years where AHD release deficit takes place
4. Average annual hydropower energy from the AHD and OAD complex (TWh/year)
5. Number of years of AHD hydropower shutdown (water level <159.0 m)
6. Average annual AHD evaporation (km^3/year)

For completeness, average annual GERD hydropower energy (TWh/year) and average annual GERD evaporation (km^3/year) will also be reported for comparison between different cases.

Due to the stochastic nature of the current investigation, none of the above indicators will be given as a single value. Instead, stochastic simulation gives the full probability distribution of each indicator. This is achieved by generating 1,000 equally probable realizations of input series, each of which spans a length of 100 years. Each of these realizations is simulated through the model and gives a single indicator value per realization. The full probability distribution of a given indicator is thus represented by the 1,000 equally probable values resulting from the simulations. It is also to be borne in mind that water deficit at AHD is to be shared by both Egypt and Sudan as per their international and bilateral agreements. The SI unit of volume (km^3) used in this study may commonly be referred to as billion cubic meters (BCM) or milliard cubic meters in some references, especially in Egypt.

When dealing with projects having a combination of considerable economic, social, and environmental impacts, decision making and mitigation measures should be based on quantiles with a reasonably low probability of occurrence. For example, a dam spillway is commonly designed for a flood with a probability of exceedance of 0.0001 (1 in 10,000) or less. This is because of the high cost of economic, environmental, and social damage that is associated with dam failure leading to very high risk. By compiling the full probability distribution of different indicators, the stochastic framework of analysis facilitates the calculation of events with different probabilities of exceedance. In this study, the 10% and 5% critical values are adopted as reasonable representative values to be considered for decision making and mitigation measures, given the high risk involved. We will thus summarize the distribution of each indicator in this study by three characteristic values. These are the expected value (mean, or average value of the indicator), and the 10% and 5% critical values. The 10% critical value is defined here as the value that has a probability of 10% for it or a worse value to occur. This may be the upper (90th) or lower (10th) percentile of the distribution based on the type of the indicator. For example, when considering deficit indicators, 10% critical means the upper (90th) percentile of the distribution, since a larger value is worse, while for power generation indicators, it means the lower (10th) percentile, since a smaller value is worse. This does not apply to some indicators that are not directly related to risk, such as evaporation and water levels, for which only average values will be reported. All the results given below should be interpreted within the stochastic framework explained above.

4 Short-Term Impacts: GERD First Impoundment

This period extends for 6 years, which is the announced period for the GERD reservoir to reach full capacity. During this period, water is abstracted to fill GERD (50 km^3 for ETR and 14.8 km^3 for LTR) in addition to initial infiltration and deep percolation, resulting in the depletion of AHD storage and increasing the risk of water shortage. Simulations indicate that the risk of AHD water release deficit within these 6 years for the base case, ETR, and LTR, is 9%, 51%, and 23%, respectively. GERD annual regulation thus increases the probability of water deficit by more than 5 times during GERD initial impoundment, while long-term regulation does by 2.5 times during the same period. The probability of AHD reservoir reaching the dead storage level within this period is 0.5%, 12.6%, and 2.5%, respectively. That is, the probability of AHD reaching the dead storage level within the GERD first impoundment period is more than 25 times that of the base case for the ETR case, and 5 times for LTR.

Table 1 gives the AHD water deficit indicators during this 6-year period. ETR would increase the average total water deficit in these 6 years from 0.4 to 7.5 km^3 (+7.1 km^3) relative to the base case, while LTR would only increase the average total deficit by 1.6 km^3. However, there is a 10% chance that the increase in water deficit would exceed 23.7 km^3 for ETR versus 6.6 km^3 for LTR. Similarly, there is a 5% chance that the increase in water deficit relative to the base case would exceed 34.1 km^3 for ETR versus 11.8 for LTR. The magnitude of these deficits is significant and would have important economic, social, and environmental implications as will be discussed later. The effect on the maximum deficit in 1 year is very

Table 1 Water deficit indicators

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	0.4	0.0	1.5
	ETR	7.5	23.7	35.6
	LTR	2.0	6.6	13.3
Maximum deficit (km^3)	No GERD	0.3	0.0	1.1
	ETR	3.9	11.1	19.1
	LTR	1.0	4.1	6.9

First impoundment period (6 years)

similar, with the increase in maximum deficit relative to the base case reaching 11.1 km^3 for ETR and 4.1 km^3 for LTR with an exceedance probability of 10% and 18.0 km^3 for ETR and 5.8 km^3 for LTR with an exceedance probability of 5%.

Table 2 gives the hydropower energy indicators for AHD. In the base case, average annual energy in this 6-year period has an average of 11.2 TWh/year. This value does not actually represent the typical long-term average since AHD reservoir starts full in this short period. For ETR, the energy drops to 9.3 TWh/year, with 17% reduction, compared with 10.1 TWh/year for LTR, with 10% reduction. The 10% and 5% critical values give reductions of 38% and 41% for ETR versus 21% and 27% for LTR, respectively.

On the other hand, AHD hydropower shutdown would increase on the average from less than 1 month in this 6-year period (72 months) to around 9.7 months for ETR, while it is around 3.2 months for LTR. At a probability of exceedance of 5%, shutdown increases from 3 months in the base case to 38 months and 23.5 months for ETR and LTR, respectively.

The simulation results also indicate that during the period of GERD first impoundment, the average annual hydropower energy from GERD is 7.7 TWh/year for ETR versus 11.1 TWh/year for LTR. In this case, LTR produces more energy since ETR tends to store more water to fill the reservoir during these 6 years, while LTR fills only the dead storage volume and then releases the average annual flow.

During the same period, average annual AHD evaporation will drop from 14.0 km^3/year to 11.2 km^3/year and 11.9 km^3/year for ETR and LTR, respectively. The reduction is 2.8 km^3/year and 2.1 km^3/year, respectively. On the other hand, average annual evaporation from GERD during the same period is 1.2 km^3/year and 1.1 km^3/year, respectively. Therefore, during these 6 years, starting with a full AHD, the annual saving in evaporation due to a reduction in AHD water level is limited to around 1.6 km^3/year and 1.0 km^3/year, respectively (9.6 and 6 km^3 for the whole period). This is of course outweighed by the amounts abstracted for GERD first impoundment.

Of particular interest to decision makers is the situation where a drought similar to that of the 1980s should occur during GERD filling. Simulations using actual data starting at the 1982/1983 flood season indicate 4 years of deficit out of six in all cases. The total deficit value is 12.1 km^3 in the base case without GERD, 57.9 km^3 for the ETR case, and 33.0 km^3 for the LTR case. That is, in the ETR case, there will

Table 2 AHD hydropower energy indicators

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Annual AHD energy (TWh/year)	No GERD	11.2	10.4	9.7
	ETR	9.3	6.5	5.7
	LTR	10.1	8.2	7.1
AHD energy shutdown (months)	No GERD	0.6	0.0	3.0
	ETR	9.7	31.0	38.0
	LTR	3.2	13.0	23.5

First impoundment period (6 years)

Table 3 Impact indicators

Indicator	Regulation	Value
Total deficit (km^3)	No GERD	12.1
	ETR	57.9
	LTR	33.0
Maximum deficit (km^3)	No GERD	7.6
	ETR	28.0
	LTR	16.2
Annual AHD energy (TWh/year)	No GERD	7.6
	ETR	4.9
	LTR	5.4
AHD hydropower shutdown (months)	No GERD	20.0
	ETR	46.0
	LTR	41.0
Annual GERD energy (TWh/year)	No GERD	–
	ETR	5.9
	LTR	7.5

First impoundment period, 1980s drought

be an additional deficit of around 45.8 km^3 more than the base case, while in the LTR case, the additional deficit would be around 20.9 km^3 only. The maximum deficit within a year that would occur during this period is 7.6 km^3 for the base case, 28.0 km^3 for ETR, and 16.2 km^3 for LTR. A summary of the impact indicators, in this case, is given in Table 3.

5 Medium-Term Impacts

After the 6-year period of GERD first impoundment, AHD reservoir water levels will be lower in general, and it will be drawn down to dead storage in some cases (12.6% of the cases for ETR and 2.5% for LTR, previous section). This will in general decrease AHD hydropower generation for an extended period, and render AHD much more vulnerable to water shortage and power shutdown during low flow periods, compared with the case without GERD. Figure 1 shows the time distribution of the probability of water deficit downstream AHD for the entire simulation period. Starting with a full AHD reservoir results in a zero probability of emptying the reservoir in the first year in all cases. The probability rises steadily in the base case to stabilize at a long-term average of about 0.24 after some 30 years. For the LTR case, the probability initially rises to around 0.25 at year 8 (base case is 0.13 at that time) and then gradually decreases to stabilize at around 0.21 (less than the base case) after some 40 years. For the ETR case, the probability rises sharply during initial filling to around 0.52 before gradually decreasing to stabilize at around 0.26 in the long-term.

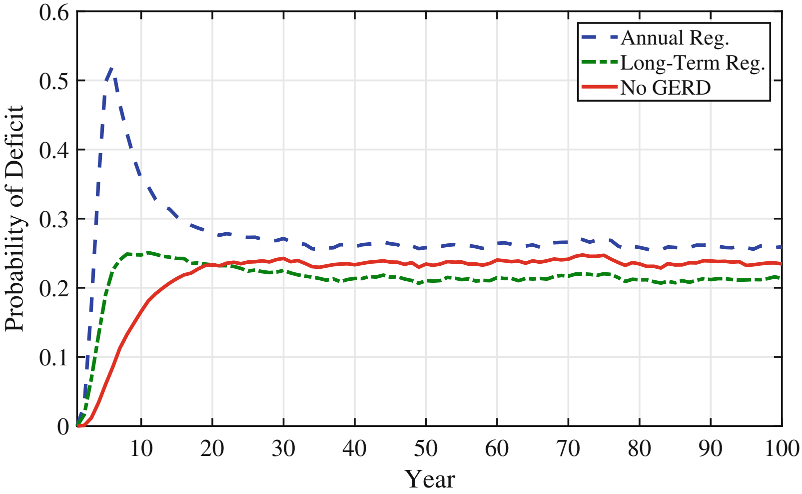

Fig. 1 Time distribution of the probability of water deficit over the simulation period

To investigate the post-filling medium-term impacts, we inspect the various indicators for 10 years starting immediately after GERD first impoundment (years 7–16). The indicators for that period are summarized in Table 4. The probability of occurrence of a deficit during this 10-year period increases from 33% in the base case without GERD to 61% for ETR and 41% for LTR. It should be noted, however, that some of these deficits are due to the application of the sliding scale rule due to low AHD levels. The chance of the reservoir reaching the dead storage level during this period increases from 6.2% in the base case to 11.9% and 7.5%, respectively. The total deficit in this 10-year period increases from 5.3 km^3 on average to 14.5 km^3 for ETR, and 8.7 km^3 for LTR, with increases of 9.2 km^3 and 3.4 km^3, respectively. There is a 10% chance, however, that the total deficit would increase by 28.9 km^3 and 14.8 km^3, respectively. At the 5% level, the increase in the total deficit would reach or exceed 29.0 km^3 and 15.0 km^3, respectively. Similarly, the maximum deficit will on average increase by 2.6 km^3 and 0.7 km^3, respectively; at the 10% level by 5.0 km^3 and 2.2 km^3, respectively; and at the level of 5% by 6.6 km^3 and 2.8 km^3, respectively.

Hydropower energy from AHD would on average be reduced from 10.3 TWh/year to 8.7 TWh for ETR and to 9.3 for LTR (16% and 9% reduction, respectively). With a chance of 10%, the reduction may exceed 2.8 TWh/year (39% of the base case) and 1.8 TWh/year (25% of the base case), respectively. With a chance of 5%, it may exceed 39% and 25% of the base case, respectively. On the other hand, the annual average GERD hydropower generation during the same period is 15.3 TWh/year for ETR and 13.4 TWh/year for LTR.

During the same 10-year period, the average AHD evaporation will drop from 12.6 km^3/year to 10.5 km^3/year for ETR and 11.0 km^3/year for LTR, with

Table 4 Impact indicators after the first impoundment (10-year period)

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	5.3	18.4	37.9
	ETR	14.5	47.3	66.9
	LTR	8.7	33.2	52.9
Maximum deficit (km^3)	No GERD	1.7	5.9	9.7
	ETR	4.3	10.9	16.3
	LTR	2.4	8.1	12.5
Number of years with AHD release deficit (years)	No GERD	1.6	7.0	9.0
	ETR	3.3	9.0	10.0
	LTR	2.2	9.0	10.0
Annual AHD energy (TWh/year)	No GERD	10.3	7.4	5.9
	ETR	8.7	4.6	3.6
	LTR	9.3	5.6	4.4
AHD energy shutdown (months)	No GERD	7.2	27.0	50.5
	ETR	23.5	77.0	94.5
	LTR	14.2	58.0	79.5
Annual GERD energy (TWh/year)	No GERD	–	–	–
	ETR	15.3	13.5	13.0
	LTR	13.4	11.1	10.4

reductions of 2.1 km^3/year and 1.6 km^3/year, respectively. On the other hand, GERD average evaporation becomes 1.9 km^3/year and 1.4 km^3/year, respectively. During this period, immediately after GERD filling, relatively lower AHD levels result in a slight saving of around 0.2 km^3/year, or 2.0 km^3 in the whole period in both cases. However, as will be seen in the next section, the situation is reversed in the long-term as the system reaches its new equilibrium state.

It would also be useful to inspect the impacts that would occur during a drought similar to that of the 1980s. In this case, the largest impacts occur when the drought starts following GERD first impoundment. For simulating this case, the actual flows starting from the 1976/1977 flood season are used, where GERD filling ends in1982/1983 and the drought period starts. Table 5 gives the impact indicators for this case.

As can be seen from Table 5, this case, where drought starts immediately after GERD first impoundment, is more severe than the case of drought occurring during filling that was covered in the previous section. The base case involves a total deficit of 47.1 km^3 during this 10-year period. With ETR, the total deficit reaches 88.2 km^3 (+41.1 km^3), and with LTR it reaches 72.9 km^3 (+25.8 km^3). The values of the maximum deficit are 15.4 km^3 for the base case, 19.5 km^3 (+4.1 km^3) for ETR, and 16.0 km^3 (+0.6 km^3). As can be seen in Table 5, 9 years out of 10 will be deficit years in the base case, with all 10 years being deficit years for ETR and LTR. The impacts of water deficit, in this case, would be devastating as can be seen.

Table 5 Impact indicators for 1980s drought following first impoundment (10-year period)

Indicator	Regulation	Value
Total deficit (km^3)	No GERD	47.1
	ETR	88.2
	LTR	72.9
Maximum deficit (km^3)	No GERD	15.4
	ETR	19.5
	LTR	16.0
Number of years with AHD release deficit (years)	No GERD	9.0
	ETR	10.0
	LTR	10.0
Annual AHD energy (TWh/year)	No GERD	5.1
	ETR	2.6
	LTR	3.2
AHD energy shutdown (months)	No GERD	62.0
	ETR	113.0
	LTR	102.0
Annual GERD energy (TWh/year)	No GERD	–
	ETR	12.6
	LTR	10.5

The hydropower energy from AHD drops from 5.1 TWh/year in the base case (less than half the average flow case) to 2.6 TWh/year (−2.5 TWh/year) for ETR, and 3.2 TWh/year (−1.9 TWh/year) for LTR. Power shutdown at AHD increases from 62 months out of 120 months in the base case to 113 months for ETR and 102 months for LTR. On the other hand, GERD hydropower energy reaches 12.6 TWh/year for ETR and 10.5 TWh/year for LTR.

6 Long-Term Impacts

As time passes, the effect of water abstracted by GERD during the first impoundment gradually diminishes, and the remaining effect would be GERD regulation and additional evaporation losses. This results in AHD operating at relatively lower water levels. We consider the impact indicators in 30 years starting after 70 years from the start of GERD first impoundment (years 71–100). By that time, the system would have reached its new equilibrium state with GERD online. Table 6 gives a summary of the impact indicators for this period.

In this case, the probability of water deficit occurring during this 30-year period is 69% for the base case, 73% for the ETR case, and 60% in the LTR case. Actual emptying of the reservoir occurs with a probability of 21% in the base case, 21% in the ETR case, and 16% in the LTR case. The average total deficit in this period reaches 25.4 km^3 for the base case, 36.3 km^3 (+10.9 km^3) for ETR, and 26.2 km^3

Table 6 Long-term impact indicators (30-year period)

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	25.4	74.1	108.5
	ETR	36.3	102.7	140.4
	LTR	26.2	80.4	118.8
Maximum deficit (km^3)	No GERD	5.3	15.6	21.6
	ETR	6.6	17.1	22.7
	LTR	4.8	13.6	20.6
Number of years with AHD release deficit (years)	No GERD	7.3	19.0	24.0
	ETR	8.1	20.0	24.0
	LTR	6.5	19.0	23.0
Annual AHD energy (TWh/year)	No GERD	9.8	7.3	6.5
	ETR	9.1	6.2	5.1
	LTR	9.4	6.6	5.6
AHD energy shutdown (months)	No GERD	33.1	101.0	138.0
	ETR	58.4	163.5	208.0
	LTR	42.7	134.0	177.0
Annual GERD energy (TWh/year)	No GERD	–	–	–
	ETR	15.2	13.9	13.6
	LTR	13.7	11.7	11.2

(+0.8 km^3) for LTR. There is a 10% chance that the total deficit will exceed 74.1 km^3 in the base case, 102.7 km^3 (+28.6 km^3) for ETR, and 80.4 km^3 (+6.3 km^3) for LTR. There is a 5% chance that the total deficit will exceed 108.5 km^3 in the base case, 140.4 km^3 (+31.9 km^3) for ETR, and 118.8 km^3 (+10.3 km^3) for LTR. As for the maximum deficit in 1 year, the average values are 5.3 km^3 for the base case, 6.6 km^3 (+1.3 km^3) for ETR, and 4.8 km^3 (−0.5 km^3) for LTR. It is to be noted that LTR tends to decrease the severity of the drought, while the total deficit increases slightly.

Hydropower energy generation at AHD averages 9.8 TWh/year in this period, decreasing to 9.1 TWh/year (−0.7 TWh/year) for ETR and 9.4 TWh/year (−0.4 TWh/year) for LTR. The corresponding critical values at the 10% level are 7.3 TWh/year for the base case, 6.2 TWh/year (−1.1 TWh/year) for ETR, and 6.6 TWh/year (−0.7 TWh/year) for LTR, and at the 5% level are 6.5 TWh/year for the base case, 5.1 TWh/year (−1.4 TWh/year) for ETR, and 5.6 TWh/year (−0.9 TWh/year) for LTR. The reduction in hydropower is a direct result of release shortages and lowered AHD water levels. The average AHD water level during this period is 170.2 m for the base case, 167.9 m for the ETR case, and 168.4 m for the LTR case.

Average evaporation losses from AHD for this period reach 11.9 km^3/year for the base case, 11.1 km^3/year (−0.8 km^3/year) for ETR, and 11.3 km^3/year (−0.6 km^3/year) for LTR. On the other hand, average evaporation from GERD reaches 1.9 km^3/year for the ETR case and 1.5 km^3/year for the LTR case. This clearly indicates that as the system reaches its new equilibrium state, the additional evaporation from

GERD exceeds the reduction in AHD evaporation by 1.1 km^3/year and 0.9 km^3/year for ETR and LTR, respectively. In other words, the combined evaporation losses from GERD and AHD (11.1 + 1.9 = 13.0 km^3/year for ETR, and 11.3 + 1.5 = 12.8 km^3/year for LTR) are larger than AHD alone (11.9 km^3/year). These results contradict the claim that GERD would result in evaporation loss savings in the system. In reality, the long-term reduction in inflow to AHD due to additional GERD evaporation results in lower AHD levels, but not low enough to reduce AHD evaporation by the same amount. On the other hand, however, the simulations do show that due to regulation by GERD, water spillage at Toshka will decrease by 0.7 km^3/year for ETR and 0.8 km^3/year for LTR in the long-term. However, the overall balance indicates a net increase in losses and a corresponding decrease in water availability.

An important issue to discuss here is the distribution of deficit and the benefit from voluntary draft reduction (the sliding scale). This may be clarified by looking at the results without applying the sliding scale reductions. Table 7 shows the water deficit indicators for the same 30-year period, but without applying the AHD sliding scale rule. Several observations can be made by comparing Tables 6 and 7. We note that when applying the sliding scale, the maximum deficit is smaller and the deficit is distributed over a larger number of years. The results also show that the probability of reservoir reaching the dead storage level reduces from 39%, 46%, and 34% without the sliding scale for the base case, ETR, and LTR, respectively, to 21%, 21%, and 16% when the sliding scale is used. This is exactly the function of the sliding scale; to reduce the probability of reservoir emptying, spread the deficit over a longer period, thus reducing the severity of drought in general. However, it can also clearly be seen that the total deficit will increase. This is inevitable because voluntarily reducing withdrawals keeps the reservoir at relatively higher levels, thus increasing evaporation losses for an extended period compared with the case without reduction. The simulations show average evaporation losses without the sliding scale of 11.6 km^3/year, 10.7 km^3/year, and 10.9 km^3/year for the base case, ETR, and LTR, respectively, increasing to 11.9 km^3/year, 11.1 km^3/year, and 11.3 km^3/year, respectively, when applying the sliding scale.

Table 7 Long-term water deficit indicators (30-year period) without sliding scale

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	16.3	54.6	88.8
	ETR	22.3	73.8	110.7
	LTR	15.4	52.2	89.8
Maximum deficit (km^3)	No GERD	5.7	20.4	25.0
	ETR	7.2	22.7	27.2
	LTR	5.0	19.2	24.1
Number of years with AHD release deficit (years)	No GERD	1.8	6.0	9.0
	ETR	2.4	8.0	11.0
	LTR	1.8	7.0	10.0

Many studies tend to report the total water deficit, in Table 7 for example, as an average annual value over the whole simulation period. In this case, the deficit would be given as 0.54 km^3/year for the base case and 0.74 km^3/year for ETR. The change in the deficit would thus be an increase of 0.36 km^3/year for ETR. It would then be argued that these are very small amounts that can be easily accommodated. However, there is no practical way to force deficit to be divided into equal annual amounts over an arbitrarily long period. On the one hand, we have a system that obeys specific physical equations governing its performance, and on the other hand, the onset of drought, duration, intensity, and total deficit are all random and cannot be easily predicted. Instead, the deficit will occur only in a few years that are usually clustered in groups. The deficit will also be randomly distributed within these years. For example, we can see in Table 7 that there will be 1 year with a maximum deficit of 7.2 km^3 on average in the ETR case, and that the deficit will be distributed (unequally) over 2.4 years on average. Such large concentrated shortages would have a much larger impact than what is implied by the theoretical average values which cannot be realized practically.

For further clarification, let us assume that Egypt water use is voluntarily cut by 0.74 km^3/year (ETR average deficit calculated above) during this 30-year period in an attempt to eliminate the deficit in the ETR case (as an alternative to applying the sliding scale). Table 8 gives the water shortage indicators in that case. We note in Table 8 that the total deficit has almost doubled in all cases. On the other hand, the maximum deficit has only slightly decreased. It can be shown that the same is true for the first impoundment case and the medium-term impacts in Tables 1 and 4 above. This shows that the notion of "average" deficit over a long simulation period is misleading and cannot be practically realized. Simply put, due to the stochastic nature of inflow, water deficit occurs in successive shocks. The severity of such shocks can be reduced by using a suitable measure such as a sliding scale (also known as "hedging") to spread the deficit over a longer period but that would in general increase the total deficit.

Finally, we raise attention to a very important issue regarding reservoir emptying and filling. We first note that the GERD reservoir is allowed to be drawn down to the dead storage in the case of LTR. This is favorable for the downstream but results in an annual average GERD hydropower energy of 13.7 TWh/year, while for the ETR case the reservoir is generally kept at higher levels to maximize hydropower and achieve a higher target (15.2 TWh/year in our simulations). Allowing GERD to

Table 8 Long-term water deficit indicators (30-year period) with 0.74 km^3/year reduction

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	35.0	65.6	94.6
	ETR	40.0	81.7	116.8
	LTR	34.4	63.5	95.8
Maximum deficit (km^3)	No GERD	5.5	19.6	24.4
	ETR	6.8	22.0	26.6
	LTR	4.9	17.8	23.1

drain to dead storage during droughts in the LTR case will result in great reduction in the impacts to the downstream as has been shown earlier. In fact, it has been argued by a number of studies that the additional GERD storage would be beneficial to the downstream countries by offering excess storage to be used during droughts. In reality, as can be seen from the results in the previous section, this is only true to some extent if the GERD reservoir is allowed to be fully drawn down (LTR case). The dilemma, however, is that because GERD does not actually offer any net savings of water as detailed above, both AHD and GERD would be drawn down to dead storage by the end of an extended drought period. For GERD to restore its hydropower production, it needs to be filled after that period, when AHD is also drained. This poses a much greater challenge than the case of GERD first impoundment when AHD is actually full (with a 90 km^3 storage buffer to absorb the impacts of GERD filling). Unfortunately, this situation is inevitable, although the exact timing of such case in the future cannot be predicted. In that case, either the downstream will suffer much greater deficits during GERD refilling or GERD would have to be filled very slowly (much longer than the initial 6 years), causing excessive GERD hydropower energy reductions.

As an example, we simulate the system using the actual flow data starting in 1931 with full AHD and Empty GERD. The evolution of the live storage in AHD and GERD for the case of LTR (which minimizes downstream impacts) are shown in Fig. 2. Although the combined storage in the system would have reached around 175 km^3 by around 1965, both reservoirs would be depleted by the end of the drought period in 1989 and refilling starts with both AHD and GERD empty. If GERD continued to support the downstream through releasing the average flow, it would remain at very low levels for around 10 years. This issue has also been discussed in the final report of the International Panel of Experts (IPOE) on GERD [11]. It is mentioned that “Whilst the GERD can stabilize downstream water supply,

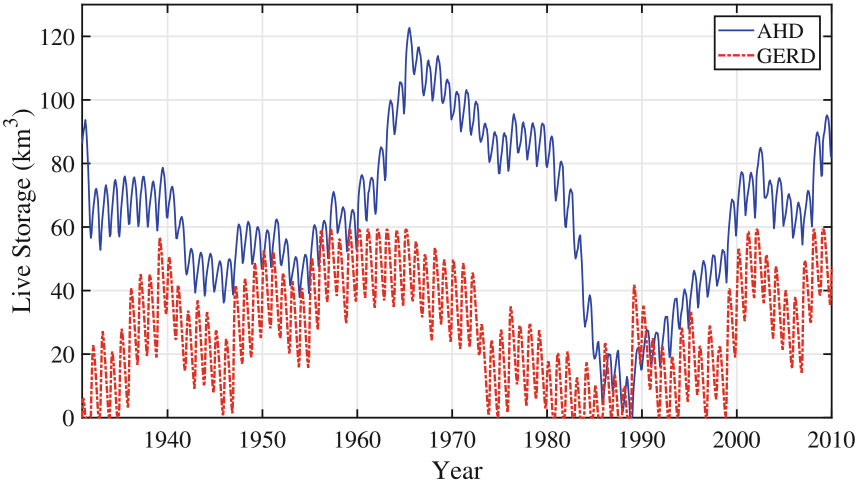

Fig. 2 Live storage in AHD and GERD. Actual flow data are starting in the year 1931

the report also shows that this may result in the GERD being drawn down to the minimum operating level for about 15 consecutive years." On the other hand, if GERD is to be refilled in a short period similar to the first impoundment, much larger deficits than those discussed earlier under GERD first impoundment would occur downstream. The 1,000 simulated cases show that both reservoirs will be empty simultaneously at some point in the future in more than in 58% of the cases without the sliding scale and 32% of the cases with the sliding scale. Furthermore, in more than 80% of the cases (without the sliding scale) and 77% of the cases (with the sliding scale), the minimum combined live storage at some point in the future would be less than 20 km^3.

7 Some Economic Implications

One of the basic deficiencies in GERD studies is the overlooking of the significant downstream social, environmental, and economic impacts. The IPOE report [11] states that "The ITEIA (Initial Transboundary Environmental Impact Assessment) does not provide an economic assessment of the GERD project from a regional perspective which takes account of the project's benefits and costs in downstream countries." For example, the water deficit amounts discussed in the previous sections, as well as AHD hydropower reductions, would have several economic, social, and environmental implications. Because performing a full-scale economic analysis is obviously beyond the scope of the current study, we will only consider some basic analysis of the economic implications to highlight their significance in a regional context.

In a study by the World Bank in 2011 [14], it was shown that the cost of adaptation measures to annual water deficit in Egypt would be US$ 11.3 billion/year for an annual deficit of 31.6 km^3 (0.36 US$/m^3). The cost increases to US$ 46.6 billion/year for an annual deficit of 61.9 km^3 (0.75 US$/m^3). Cost thus increases exponentially as the deficit increases. An exponential relationship for the adaptation cost C in US$ billion can be fitted which can be expressed as: $C = 4.7756[\exp(0.0384\, x) - 1]$, where x is the deficit in km^3. For this study, we will assume an analysis horizon of 50 years (including GERD first impoundment period) to compare the downstream costs and GERD net benefits. Hydropower energy selling price is assumed to be US$ 0.07 per kWh. An average discount rate for public projects of 6% is also assumed (usually between 4 and 8% [15]). Table 9 shows the water deficit and hydropower energy indicators for the whole 50-year period of analysis.

As per the exponential cost relationship that given above, the average maximum deficit in 1 year in Table 9 of 9.6 km^3 in the case of ETR would have an adaptation cost of around US$ 2.13 billion. The 22.7 km^3 (10% probability) would cost around US$ 6.64 billion, while the 28.3 km^3 (5% probability) would cost around US$ 9.38 billion. The corresponding values for the base case are US$ 1.26, 4.87, and 6.95 billion, respectively, and for the LTR case are US$ 1.28, 4.43, and 6.77 billion,

Table 9 Impact indicators for the analysis period of the first 50 years

Indicator	Regulation	Expected value	Critical 10%	Critical 5%
Total deficit (km^3)	No GERD	33.6	102.2	140.9
	ETR	62.2	165.2	204.2
	LTR	40.4	124.5	160.2
Maximum deficit (km^3)	No GERD	6.1	18.3	23.4
	ETR	9.6	22.7	28.3
	LTR	6.2	17.1	23.0
Annual AHD energy (TWh/year)	No GERD	10.1	8.2	7.4
	ETR	9.1	6.6	5.9
	LTR	9.6	7.2	6.3
Annual GERD energy (TWh/year)	No GERD	–	–	–
	ETR	14.4	13.3	13.0
	LTR	13.4	11.7	11.2

respectively. The additional costs of adaptation for the maximum year only due to GERD relative to the base case for the ETR case are thus US$ 0.87, 1.77, and 2.43 billion. Similarly, AHD energy would be decreased by 1 TWh/year for ETR and 0.5 TWh/year for LTR. The energy cost for 1 year becomes US$ 0.07 billion/year for ETR and US$ 0.04 billion/year for LTR. These are the costs of adaptation and energy reduction for a single year. The present worth (PW) of all deficit costs will depend on the distribution of deficit in the future. Table 10 gives the results of the PW of water deficit adaptation costs as well as AHD hydropower revenue loss, both relative to the base case, for the analysis period of 50 years. Similar to impact indicators, the values in Table 10 are calculated from the distribution of costs derived from 1,000 random simulations.

The cost of GERD is taken as US$ 4.8 billion [7] (which could increase to US$ 7.0 billion [16]), while the annual operation and maintenance cost is assumed as 2% of GERD cost annually [17]. The cost of power transmission infrastructure, which has not been yet assessed in the literature, will not be considered here. Based on these assumptions, the PW of GERD costs and revenues for the 50-year analysis period can be calculated as in Table 11.

It can be concluded by comparing Tables 10 and 11 that AHD impact costs are considerable compared to GERD costs and revenues. There is a great risk in the case of ETR that AHD impact costs would exceed GERD benefits as can be seen by comparing the costs and benefits of the 10% and 5% critical values. In fact, out of 1,000 simulated cases, there are 231 cases (23.1%) where costs exceed benefits for the ETR case, compared to 38 cases (3.8%) only for LTR.

For the particular case of 1980s drought, AHD impact costs are much higher. Tables 12 and 13 give the costs for the cases of drought during GERD first impoundment and drought right after GERD first impoundment, respectively. It is to be noted that due to the limited extent of the historical time series in both cases, the analysis periods are only 29 and 35 years, respectively. Also, deficits occur 6 years later in the latter case, so that the PW of the cost is relatively smaller. However, in both cases the downstream costs are very large.

Table 10 PW of AHD impact costs (US$ billion) relative to the base case

Item	Regulation	Expected value	Critical 10%	Critical 5%
Water deficit adaptation additional cost	ETR	2.87	7.78	9.68
	LTR	0.73	2.67	3.69
AHD energy revenue decrease	ETR	1.54	2.57	2.68
	LTR	0.90	1.59	1.75
Combined AHD impact cost	**ETR**	**4.41**	**10.13**	**12.19**
	LTR	**1.63**	**4.30**	**5.40**

Table 11 PW of GERD costs and revenues (US$ billion)

Item	Regulation	Expected value	Critical 10%	Critical 5%
GERD costs (initial + O&M)		6.31	6.31	6.31
GERD revenues	ETR	14.15	12.99	12.65
	LTR	14.06	12.21	11.76
GERD net benefit	**ETR**	**7.84**	**6.68**	**6.34**
	LTR	**7.75**	**5.90**	**5.45**

Table 12 PW of AHD impact costs (US$ billion), 1980s drought during GERD first impoundment

Item	Regulation	Cost
Water deficit adaptation additional cost	ETR	12.09
	LTR	5.05
AHD energy revenue decrease	ETR	1.59
	LTR	1.48
Combined AHD impact cost	**ETR**	**13.68**
	LTR	**6.53**

Table 13 PW of AHD impact costs (US$ billion), 1980s drought following GERD first impoundment

Item	Regulation	Cost
Water deficit adaptation additional cost	ETR	7.14
	LTR	3.26
AHD energy revenue decrease	ETR	2.04
	LTR	1.22
Combined AHD impact cost	**ETR**	**9.18**
	LTR	**4.48**

Although only a few elements of the economic analysis have been considered here, it is clear from the results shown above that the downstream costs related to AHD water shortage and hydropower energy reduction alone are of the same order of magnitude as GERD net benefits. It also appears that GERD operation for hydropower maximization (ETR) may not be economically justified in a regional context given the large downstream risks. Operating GERD as a long-term storage reservoir (LTR) poses relatively lower risks, but it would be hard to assess the economic attractiveness of GERD in a regional context under this assumption without a thorough regional economic analysis.

8 Summary and Conclusions

This study investigated the impacts of the Grand Ethiopian Renaissance Dam (GERD) on the Aswan High Dam (AHD). A stochastic framework was adapted to account for the Nile flow overyear variability as identified by Hurst, which is characterized by clusters of high values and others of low values. Two basic modes of operation of GERD were considered. The first assumes annual operation to maximize hydropower with initial filling to a storage of 50 km^3, and the second assumes long-term regulation by releasing a constant annual volume equal to the long-term mean flow minus evaporation losses, with initial filling up to the dead storage of 14.8 km^3 only. We have assumed a business as usual situation where Egypt and Sudan continue to withdraw their full shares, applying the sliding scale rule when necessary to reduce the probability of reservoir emptying. Coordinated multi-reservoir operation of AHD and GERD has not been considered in this study.

The following conclusions can be made based on the results of the simulations discussed above:

1. For both GERD regulation modes considered in this study, there is no actual saving in water for the downstream countries. Consistent with the physical laws that govern the water balance in the system, the simulations show that water abstracted by GERD affects all other water balance components. In particular, evaporation from GERD does not only affect evaporation from AHD, and does not become compensated by the reduction of evaporation from AHD, either. Instead, the reduction in AHD inflow caused by GERD is manifested as AHD evaporation reduction, Toshka spill reduction, as well as an increase in release deficit downstream of AHD, where the proportions of each of these components are dictated by the properties of the system. Overall, the simulations indicate a net increase in losses in the system with the addition of GERD in the long-term.
2. Operating GERD for power maximization, which requires the abstraction of large amounts of water for GERD first impoundment and involves relatively higher GERD evaporation losses (compared to long-term regulation), will severely affect AHD. It will result in increasing water deficit well beyond the deficit amounts due to natural Nile flow variability and reducing hydropower energy production from the AHD and Old Aswan Dam hydropower complex due to a reduction in both water releases and water levels.
3. The impacts due to GERD are most severe during and shortly after the first impoundment till the system regains its balance. During this period, the AHD

system is most vulnerable to the impacts of natural droughts. The simulations show that the impacts would be most severe should the drought period of the 1980s recur during, or shortly after GERD initial filling.

4. GERD operation as a long-term storage reservoir reduces the impacts relative to the operation for power maximization. However, this still causes a significant increase in water deficits and hydropower reduction in the short term. In the long-term, this mode of operation helps to partially reduce the severity of droughts relative to the base case, with a slight increase in total deficits, due to the net decrease in system water availability.
5. A very limited economic analysis reveals that AHD costs due to water deficit and hydropower energy reduction are of the same order of magnitude as GERD net benefits. Considering these costs, as well as other costs not covered in the current study, may give a totally different view of the economic viability of GERD in a regional context. This is clearly related to, and may also affect, the operating policies of GERD, and probably those of AHD.
6. The long-term storage mode of GERD operation (LTR) involves the minimum initial storage and causes the least change in natural flow quantities due to relatively lower GERD evaporation losses while reducing the annual variability in the Blue Nile contribution. On the other hand, power maximization (ETR) requires a much larger initial filling and involves higher evaporation due to higher GERD water levels, thus causing more severe impacts. If a cooperative operation is considered, GERD is expected to be operated at higher levels during above-average years but would need to be drawn down to supplement release during droughts. This represents a situation somewhere between the two basic modes of GERD operation considered in this study, and the impacts would, in general, be halfway between those reported.
7. Because GERD does not offer water saving in the long-term, and due to full water utilization by downstream countries, it is inevitable that both GERD and AHD would be drawn down to or near their dead storage at some point in time in the future. This would be caused by an extended drought period similar to or worse than the 1980s period. Refilling both reservoirs would be more challenging than the current situation of GERD first impoundment while AHD is currently almost full.

9 Recommendations

As has been shown, depending on its initial impoundment plan and operation policy, GERD can have significant impacts on the downstream, for which the associated costs have not been taken into consideration. In particular, operating GERD solely for hydropower energy maximization involves extremely high risks for the downstream. Decision makers should be aware that, due to the random nature of droughts, filling plans, operation policies, adaptation measures, safeguard policies, and contingency plans all need to be in place before the start of the actual filling and operation of GERD. Without such proper planning, it may not be possible to successfully manage the severe consequences of an extended drought once it occurs. A complete management plan is thus needed to minimize downstream risks, a crucial component of which is a comprehensive regional economic, social, and environmental impact assessment study. Considering the above results, studying the impact of future climatic change on Nile flow is of utmost importance, as any future decline in Nile flow will further complicate the water shortage problem.

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Model-Based Optimization for Operating the Ethiopian Renaissance Dam on the Blue Nile River

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Contents

Abstract Ethiopia has proposed different plans and conducted studies for dam projects on the Blue Nile, but the storage capacity required for such large dams is much higher than the capability of the Blue. Ethiopia unilaterally announced its plan to build the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile at the very same location of the Border Dam. It increased the storage capacity from 11.1 to 74 billion cubic meter (BCM), which represents 1.5 times the annual flow of the Blue Nile at the Sudanese border and produces 6,450 MW of hydropower. The dam

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will have negative impacts on the downstream countries, especially shortage in water supply and hydropower generation during filling and operation.

The main purpose of this chapter is to develop a methodology using the GERD-AHD SIM model to determine the best operating policy for the Renaissance Dam on the Blue Nile that achieves minimum impact on the Aswan High Dam (AHD). The main objectives should be achieving a minimum water deficit in the downstream and a maximum power generation from both GERD and AHD.

The results of the model were tabulated and analyzed using the mentioned criteria to obtain the best long-term regulation policies for GERD. The main two factors that affect the management of AHD due to the regulation policy of GERD are the annual total water deficit downstream AHD and the generated energy from AHD. Those two evaluating factors were taken as the most critical criteria for arranging and choosing the best scenarios based on the results of the model.

Different scenarios were selected and tested. Each scenario has the following inputs: the initial levels of both GERD and AHD, the average AHD level, the average inflow to AHD, the annual evaporation of AHD and GERD, the energy produced from the two dams, the maximum water deficit downstream AHD, the number of water deficit downstream AHD, the number of shutdowns of AHD hydropower station, and the total water deficit.

It is clear that the cooperative management scenarios which preserve water storage in GERD for the need of the downstream countries represent the best regulation scenarios. Comparing cooperative and noncooperative scenarios shows this fact explicitly.

Keywords Blue Nile, GERD, High Aswan Dam, Optimization, Renaissance Dam, Simulation model

1 Introduction

Egypt is located in an arid zone where rainfall is rare (no more than 15 mm/year on average), and more than 97% of the water supply of Egypt comes from the Nile River that originates outside its borders. The Blue Nile Basin is the primary watershed that contributes 58–62% of the water that arrives at Aswan High Dam Lake. Although population growth, agricultural expansion, as well as industrial development and a rise in the standard of living press for additional water resources, the quota for withdrawal from the Nile River is fixed at 55.5 billion cubic meter (BCM) since 1959.

The river system is formed by two distinct major tributaries, commonly called the Blue Nile and the White Nile, which merge at Khartoum, Sudan, to form the main Nile. The upper Blue Nile Basin contains the considerable untapped potential for irrigation and hydropower development and expansion. Obviously, the activities on the Blue Nile, such as dams and irrigation, would cause considerable changes in water arrival to Egypt in terms of quality and quantity and could have significant impacts on Egypt's economic, social, and environmental conditions.

The Nile River is the longest river in the world. This unique river traverses more than 6,700 km from its headwaters to its delta on the Mediterranean Sea. The Nile Basin covers an area of about 3.18 million km^2, including 11 countries of Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda. The Nile encompasses three main water sources: the Eastern Nile basin, the Equatorial Lakes basin, and the Bahr el Ghazal basin [1].

The Low Aswan Dam (LAD), established in 1902, Sennar Dam (1925), and Jebel Aulia Dam (1937) were constructed under British colonial influence. They have a vision of coordinated management that would extend the availability of seasonal floodwaters in Egypt and open up the agricultural potential in Sudan with the Gezira irrigation scheme (Tvedt, 2004). The Khashm el-Girba Dam (1964), Roseries Dam (1966 and 2013), and Aswan High Dam (AHD, 1970) were constructed under the auspices of 1959 treaty between the two countries (Nile Treaty 1959).

The relatively recent development projects of Ethiopia's Tekeze Dam (2009), Tana Beles (2010) and Sudan's Merowe Dam (2009), and the dam complex of Upper Atbara and Setit (2017) have been effectively independent of international coordination during construction and operation, with hydropower as essentially their only purpose.

The rivers comprising the Eastern Nile form an important shared resource linking Ethiopia, Sudan, and Egypt. The Nile is crucial for the social, economic, and environmental development of the countries, within which food production and electric power generation are key elements. There are significant constraints to economic growth in the region: extreme poverty, rapid population growth, and environmental degradation being the primary ones.

Recurrent droughts, intense flooding, and massive erosion are all features of the Eastern Nile basin and have major social and economic impacts. This climatic variability makes managing the water resources more difficult, and this may be further exacerbated as expected climate change develops through this century. Water management will certainly become increasingly challenging with increasing demands for food production, domestic water, energy production, and others.

The hydrological unity of the Eastern Nile offers vast opportunities for cooperation to improve food production, better manage the environment, reverse environmental degradation, conserve natural resources by using them more efficiently, and contribute to the economic and social development of the region.

Ethiopia possesses ample water resources and a great potential for hydropower generation. Thus, the Ethiopian government is planning to make use of the hydropower potential in different river basins in Ethiopia in general, and in the Blue Nile Basin in particular, for improving the living standards and advancing development. In that context, the Blue Nile Basin comes at the top of the priority list of the Ethiopian government, where numerous studies have been carried out for development in the Blue Nile Basin.

In 1964, the US Bureau of Reclamation conducted a study on behalf of the government of Ethiopia that identified 33 projects in the Blue Nile Basin [2]. Four of them are potential dam sites on the main Blue Nile, including Border Dam, which has now become the location of the Grand Ethiopian Renaissance Dam (GERD). In the Ethiopian master plan project [3], Mabil Dam is replaced by Biko Abo (see Fig. 1). Ethiopia began the GERD construction on April 2, 2011. It has a planned height of 145 m and full supply elevation of 640 m above sea level (masl), creating a reservoir of 74 billion cubic meters (BCM). The filling is considered complete when the reservoir level reaches 640 masl (see Fig. 2).

In 2008, the Eastern Nile Power Trade Studies carried out pre-feasibility studies at three sites in the Blue Nile Gorge under the auspices of the Nile Basin Initiative/ Eastern Nile Subsidiary Action Program (NBI/ENSAP) comprising Egypt, Ethiopia, and Sudan. These studies confirmed the suitability of many sites in the region for hydropower generation and for the promotion of interregional trade in power supplies. One of the proposed projects was the Border Dam that is located 15 km from the Sudanese borders with 14.5 BCM storage capacity.

The AHD is operated primarily to meet Egypt demands that total 55.5 BCM per year. The minimum elevation for power generation and downstream releases is 147 m (31.9 BCM), and the elevation range from 175 to 182 m (121–167 BCM) is

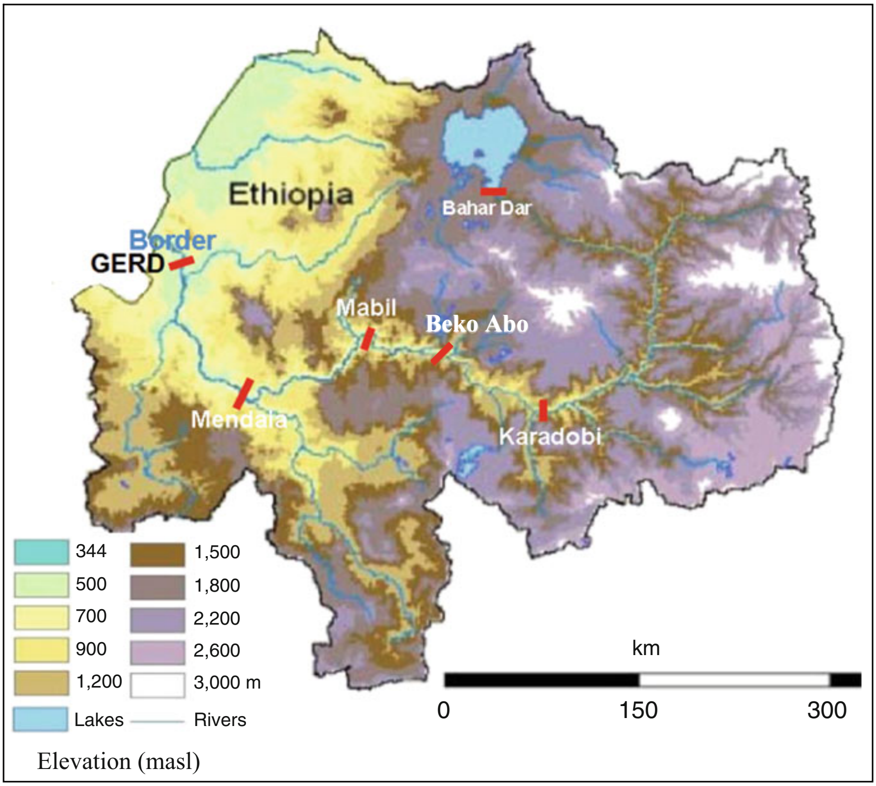
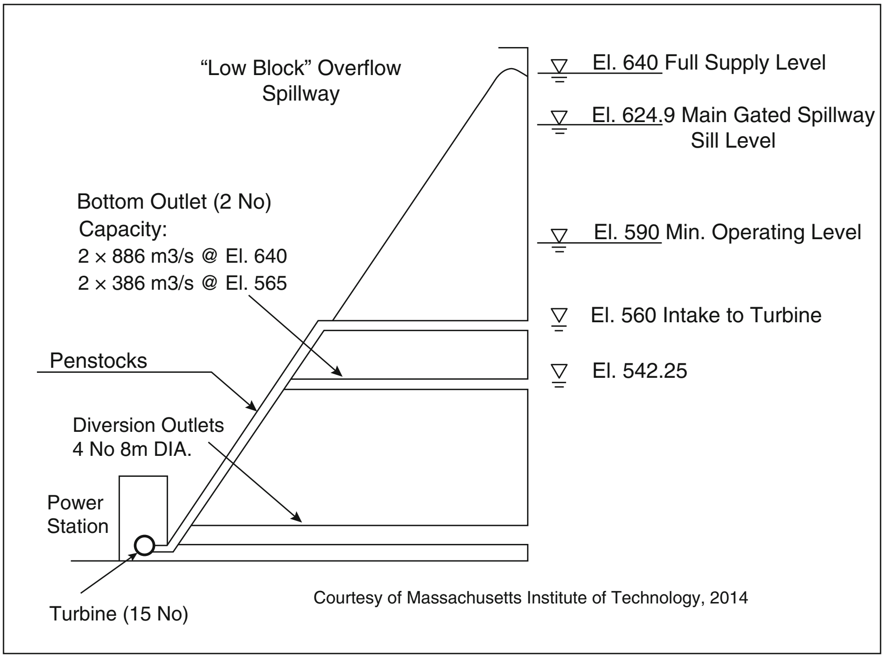


Fig. 1 Location of Grand Ethiopian Renaissance Dam (GERD) and major proposed dams on the main Blue Nile [4]



Courtesy of Massachusetts Institute of Technology, 2014

Fig. 2 Cross-section of the Grand Ethiopian Renaissance Dam with assumed hydraulic capacities [5]

reserved for emergency storage or flood protection operations. Reservoir elevations above 178 m are assumed to begin spilling into the Toshka canal [6].

Several authors had developed computer models that simulate the long-term development of the Eastern Nile basin. Some of these studies include the following: Guariso and Whittington [7], Yao and Georgakakos [8], Ahmed [9], ENTRO [10], EDF and Wilson [11], Georgia Water Research Institute [12], Blackmore and Whittington [13], Block and Strzepek [14], McCartney and Girma [15], and Arjoon et al. [16], and recently efforts have been conducted to analyze possible GERD filling strategies: Bates et al. [17], Wheeler et al. [18, 19], Sileet [20, 21], King and Block [22], Mulat and Moges [23], and Zhang et al. [24].

2 Problem Statement

The Grand Ethiopian Renaissance Dam, formerly known as the Millennium Dam, is a gravity dam under construction on the Blue Nile River, about 20 km east of Sudan border in the Benishangul-Gumuz region of Ethiopia. At 6,000 megawatts (MW), the dam will be the largest hydroelectric power plant in Africa when completed, as well as the seventh largest in the world sharing the spot with Krasnoyarskaya in Russia.

The reservoir, with a total storage of 74 BCM, will be one of the continent's largest. The dam will be a 145-m-high, 1,800-m-long gravity-type dam composed of roller-compacted concrete (RCC) and will have two powerhouses, one on each side of the spillway. The right power house will contain ten 375 MW Francis turbine-generators, while the left will contain five. Complementing the dam and reservoir will be a 5-km-long, 50-m-high saddle dam closing a gap in the reservoir (see Fig. 3).

The impacts of this dam on the most downstream water users in Egypt need to be assessed and determined in the spirit of cooperation toward achieving benefits for all and reaching a win-win solution with the no-harm principle maintained. The Aswan High Dam (AHD) located in southern Egypt was completed in 1968 with an over-year live storage capacity of 90 BCM and a large reservoir extending for 500 km along the Nile River covering an area of 6,000 km^2. In addition to the live storage component, a dead storage of 31 BCM and a flood control capacity of 41 BCM have been accommodated.

The AHD contributed greatly to the economic development of Egypt by supplying 15% more irrigation water and about 2,000 MW hydroelectricity and protecting the lower reaches of the Nile from flood disasters. The live storage

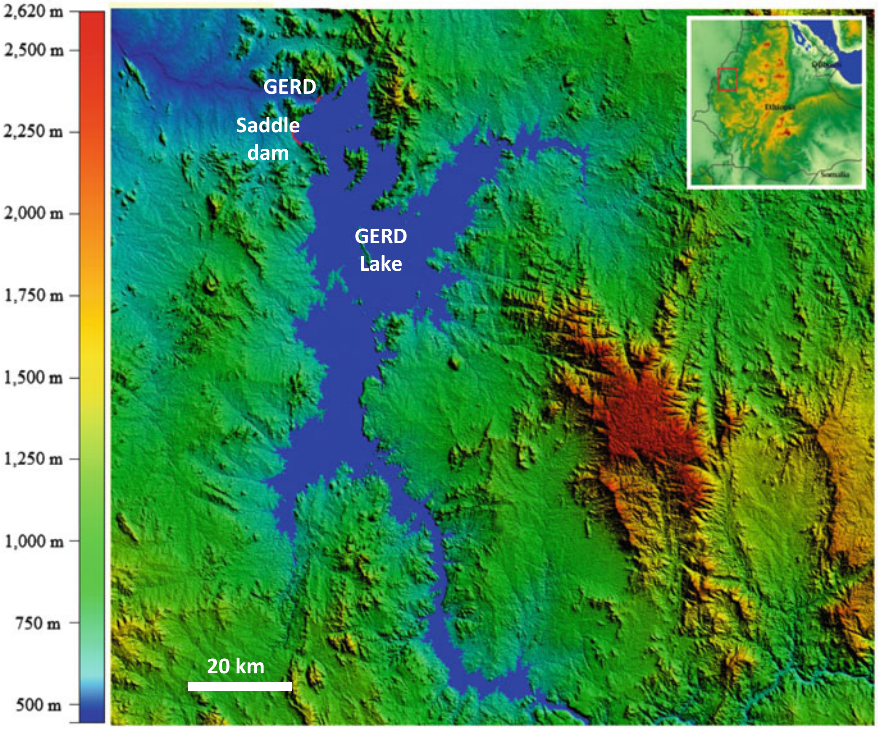


Fig. 3 Digital elevation model (DEM) of the GERD, Saddle Dam, and GERD lake at the maximum operating level of 640 masl using ASTER Global DEM

room of the dam is considered full at a level of 175 m, and then the room of the flood control storage starts and extends up to the level of 182 m. AHD starts to receive the flood water by August every year where the upstream level should not exceed 175 m to give flood control room to accommodate the new flood. Otherwise the dam and Toshka spillways would be used to rescue the dam from overtopping.

The AHD is designed based on an average natural flow of the Nile at Aswan estimated at 84 BCM. Most of the flood water comes during August, September, and October as a response to the seasonal flood of the Ethiopian Plateau constituting 85% of the total annual flood, where the remaining 15% comes from the Equatorial Lakes Plateau distributed over the whole year. Therefore, any developments on the Blue Nile, the main stem of the Ethiopian Plateau, will certainly impact AHD in terms of water availability, hydropower generation, and operation. The Blue Nile is characterized by the fact that 80% of its yield occurs during the flood months (July to October), which makes it a highly seasonal river.

The operation of the Renaissance Dam, if not coordinated with the downstream countries, will have a significant negative effect on the distribution of water arriving at AHD during the year. The Nile flow in August to October will be significantly reduced, while it will be increased in the remaining months in addition to evaporation losses from the Renaissance Dam. This will result in permanent loss of water and reduction of hydropower generation. In particular, operation rules during dry periods need to satisfy both water demand and hydropower needs.

3 Objectives

The research question in this paper can be formulated as follows: What is the optimal long-term operating strategy of the Renaissance Dam for minimum impact on the operating policy and the power generation from AHD complex taking into account maximizing power generation from the Renaissance Dam?

Therefore, the main objective of this study is to addresses the various long-term impacts of the project throughout the operating stage using different scenarios with different hydropower generation policies. This study does not consider the short- to medium-term impacts due to the first impoundment of the GERD, which have been addressed elsewhere in the literature. The study will try to adopt operation policies for the Renaissance Dam that don't affect the operation of AHD in the long-term.

4 Methodology

This chapter develops a methodology based on a coupled simulation-optimization approach for determining the best operating policy for the Renaissance Dam on the Blue Nile with minimum impact on the complex of AHD in terms of its storage, water levels, and generated hydropower. It takes into consideration ensuring maximization of power generation from both AHD and Renaissance Dam and minimizing water shortage released downstream AHD.

The system of the Renaissance Dam will be set in the GERD-AHD simulation model (GERD-AHD SIM, 2013) which is a recently developed by Water Resources and Energy Management (WREM) International Inc. to investigate the downstream impacts of the Grand Ethiopian Renaissance Dam (GERD) on AHD.

The model simulates the flow of water through the various system nodes, reaches, and reservoirs. In keeping with its planning purpose, the model time resolution is 10 days. The simulation model includes a routing model for each river reach and regulation rules for each reservoir. Two types of reservoir regulation rules are included: (1) simple static rules and (2) dynamic multi-reservoir coordination rules.

MATLAB, a computer programming language and interactive environment for numerical computation and visualization, was used to input the time series of used stations automatically into the database of GERD-AHD SIM model. After finishing the simulation runs by GERD-AHD SIM model, MATLAB was again used as a post-processor to extract the simulation results from the database and to perform analysis on the output results of the simulation model.

It is targeted to identify a group of operation rules for the GERD that maintains minimum impacts on AHD in terms of the water deficit downstream AHD and the generated power of the Aswan hydropower complex. The best operating rules will be arranged per the flood period type, storage capacity of GERD, and the initial levels of both dams.

5 Simulation Model Description

The simulation model simulates the response of the Eastern Nile system including the GERD, five other existing reservoirs (Roseires after heightening, Sennar, Khashm el-Girba, Merowe, and Aswan High Dam (AHD)/Old Aswan Dam (OAD complex)), and the river reaches connecting the river network. The software consists of a user interface, a database, several utility tools, and the simulation model [25]. The current version of the GERD-AHD SIM includes one simulation/assessment applications, which can be used to simulate the GERD filling or long-term regulation. Simple reservoir regulation rules define reservoir releases as a function of reservoir elevation, inflow, irrigation demand, or time of the year, or some combination of these parameters.

The Nile-DST can help in selecting and defining any of these options. These regulation rules are widespread, but they are simply because they relate reservoir release to a few parameters of the same reservoir and, possibly, of nearby reservoirs. Dynamic multi-reservoir coordination rules are also possible and are available through the system optimization model. System optimization encompasses four sub-models pertaining to (a) streamflow forecasting, (b) river and reservoir simulation, (c) reservoir optimization, and (d) scenario assessment.

A historical time series of the natural flow of the Nile and data of AHD was used to study the full range of the indicators, which are affected by the pattern of the sequence of the Blue Nile flows after constructing the Renaissance Dam. The used

Fig. 4 Rivers, water projects and irrigated lands in western Ethiopia, Sudan, and southern Egypt [25]

time series cover different periods of the Nile flow including average, wet, drought periods. Also, different initial boundary conditions of GERD and AHD were used to assess the best operating scenarios. Figure 4 shows the interface of GERD-AHD SIM.

5.1 Models and Applications

The current version of GERD-AHD SIM includes only one application, which can be used to simulate the GERD filling process or the long-term system regulation. The assessment model is used to assess the system performance under various combinations of constraints and regulation policies.

5.2 System Description

To facilitate the GERD impact assessment, a comprehensive simulation model of the Eastern Nile system was used. This model encompasses the Eastern Nile system shown in Fig. 5 and includes the following reaches:

- White Nile inflow contribution at the exit of Jebel el Awlia (Mogren)
- Blue Nile from and including the GERD (near Diem) to Khartoum
- Atbara River from the Khashm el-Girba Dam to the junction with the main Nile
- Main Nile from Khartoum to Dongola
- Aswan High/Old Aswan Dam complex including the downstream water requirements

5.3 Assessment Scope

Beyond the filling period, the GERD is expected to influence the Blue and main Nile flow regimes in far-reaching and unprecedented ways, thus raising questions of critical national and regional importance that may include:

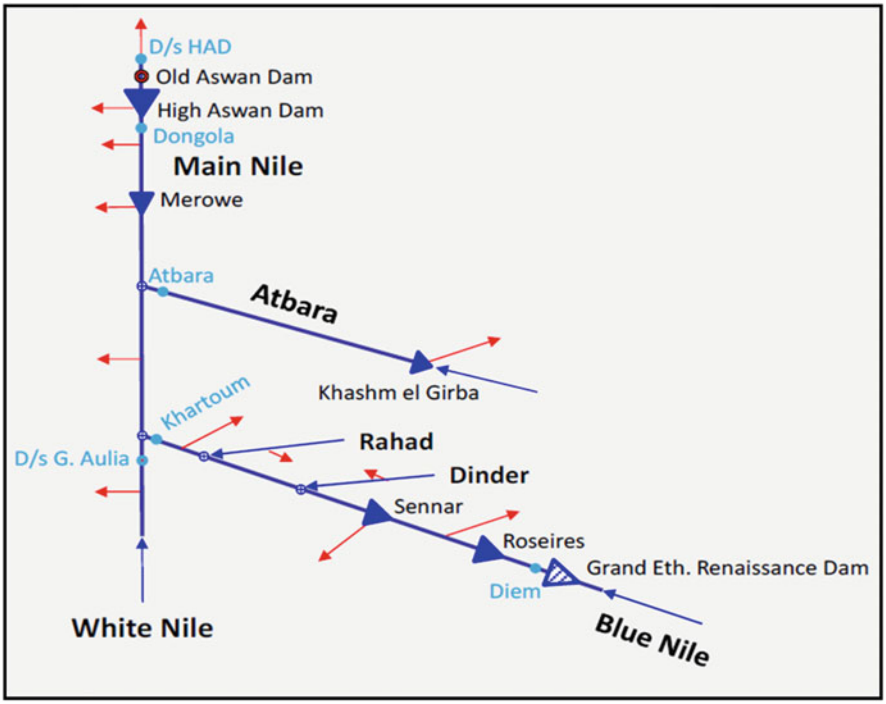


Fig. 5 Schematic of system model [25]

1. How will the seasonal Nile flow regime be altered?
2. What are the impacts, benefits, and risks of the altered flow regime for Egypt?
3. How do these impacts, benefits, and risks depend on the GERD management policy?
4. Is there a management policy that mitigates the GERD impacts and risks and maximizes its benefits for all Eastern Nile countries?

The assessments described herein provide quantitative answers to these questions and explore the viability of a sustainable regional management plan. The scenarios assessed in this study fall into three categories:

1. Long-term regulation using the time series of the entire record period 1912–2011, representative of an average flood period, and given the notation (A)
2. Long-term regulation using the time series of 1960–2059 (by wrapping the 1912–1959 record to represent 2012–2059), representative of a high flood period of the same record length, and given the notation (B)
3. Long-term regulation using the time series of 1980–2079 (by wrapping the 1912–1979 record to represent 2012–2079) representative of a low flood period of the same record length, and given the notation (C)

It should be noted that the model is governed by the following limiting factors:

1. The level of dead storage of GERD is 590 m.
2. The level of dead storage of AHD is 147 m.
3. The minimum level of AHD for power production is 159 m.
4. The maximum level of water upstream GERD is 640 m.

Several GERD regulation policies are formulated and assessed throughout this study. The baseline policy is focused on Ethiopian hydropower interests with GERD operating to meet a constant energy target. Other policies are also implemented aiming to balance Ethiopian as well as downstream interests and to provide relief during periods of water shortage. This relief may be enabled by a certain amount of GERD storage (e.g., 10 or 20 BCM) reserved for this purpose as a cooperative regulation policy.

5.4 Assessment Criteria and Measures

For the simulations using inflow series of the above three categories, several criteria are used to assess the (GERD-AHD SIM) model response under each scenario. These criteria include:

1. Reservoir levels
2. Reservoir net evaporation losses
3. River flow hydrographs
4. River losses
5. Energy generation at all hydropower sites

6. Firm energy generation at GERD and AHD
7. Water supply deficits in Egypt

The performance of each scenario against these criteria is measured using various statistics, such as average and extreme values, as well as the entire frequency distributions.

6 Results and Discussion

Several scenarios A, B, and C under the above mentioned three categories are formulated and assessed in detailed simulation experiments. The model simulates the response of the Eastern Nile system including the GERD, five other existing reservoirs (Roseires after heightening, Sennar, Khashm el-Girba, Merowe, and Aswan High Dam (AHD)/Old Aswan Dam (OAD complex)), and the river reaches connecting the river network. A selected number of regulation scenarios have been examined.

The scenarios share the following common elements:

1. Simulation time step, 10 days
2. Reservoirs and initial levels (meters above sea level (masl) (Table 1))
3. Egyptian irrigation target, 55.5 BCM/year
4. Sudan annual share, 18.5 BCM/year

Tables 2, 3, and 4 show the main indicators that represent the output results of the model for categories A, B, and C, respectively. Each table covers 27 scenarios using the data of the time series of the relevant type of flood, different operating rules of GERD, and different initial levels of AHD and GERD.

Among the primary indicators shown in the following tables are the total water deficit downstream Aswan High Dam (DS AHD) and the average annual energy production from AHD. These two primary indicators will be used for determining the best operating policies for GERD.

6.1 Analysis of Model Results

Assessments using cooperative regulation policies, in which a certain amount of GERD storage is reserved to mitigate Egyptian water shortages, the GERD will

Table 1 Reservoirs and initial levels (masl)

Reservoir	Initial level (masl)
GERD	590, 620, 622
Roseires	490
Sennar	420
Khashm el-Girba	473
Merowe	300
AHD	160, 165, 170

Table 2 The results of the primary indicators that represent the output results of the model for category A (normal flood)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DS AHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD	Total water deficit DS AHD (BCM)
1	1A	EN. target	160	620	161.89	64.0	14,285	1.486	8.8	4,778	16.42	6	35	62.06
2	2A	EN. target	160	640	162.24	64.3	14,425	1.509	8.9	4,942	16.42	4	33	45.14
3	3A	EN. target	165	620	162.01	64.0	14,285	1.486	8.8	4,830	16.42	5	35	49.60
4	4A	EN. target	165	640	162.74	64.3	14,425	1.509	9.1	5,286	16.42	4	29	45.14
5	5A	EN. target	170	620	162.49	64.0	14,285	1.486	9.0	5,058	16.42	4	32	45.14
6	6A	EN. target	170	640	163.29	64.3	14,425	1.509	9.3	5,529	16.42	4	26	45.13
7	7A	RS. 20	160	620	161.05	64.4	14,306	1.481	8.6	4,463	14.85	4	40	22.72
8	8A	RS. 20	160	640	161.91	64.6	14,733	1.557	8.9	5,143	15.06	3	30	31.32
9	9A	RS. 20	165	620	161.61	64.4	14,151	1.449	8.7	5,017	14.91	3	31	21.00
10	10A	RS. 20	165	640	162.41	64.6	14,761	1.561	9.0	5,374	15.08	3	28	30.66
11	11A	RS. 20	170	620	162.10	64.3	14,629	1.550	8.9	5,252	15.00	3	29	30.25
12	12A	RS. 20	170	640	162.99	64.6	14,761	1.561	9.2	5,654	15.08	3	24	30.65
13	13A	RS. 10	160	620	161.90	64.5	14,281	1.464	8.8	5,121	16.52	6	30	41.90
14	14A	RS. 10	160	640	162.66	64.8	14,425	1.493	9.1	5,466	15.14	4	26	40.48
15	15A	RS. 10	165	620	161.96	64.5	13,957	1.401	8.8	5,231	14.92	3	28	22.97
16	16A	RS. 10	165	640	163.17	64.8	14,427	1.493	9.2	5,717	15.13	4	23	39.24
17	17A	RS. 10	170	620	162.87	64.5	14,311	1.483	9.1	5,572	15.13	4	25	39.45
18	18A	RS. 10	170	640	163.72	64.8	14,427	1.493	9.4	6,026	15.13	4	19	39.27
19	40A	EN. target	160	590	161.74	63.7	14,210	1.482	8.8	4,689	30.99	7	37	83.45
20	41A	EN. target	165	590	161.86	63.7	14,210	1.482	8.8	4,755	20.58	6	36	70.33
21	42A	EN. target	170	590	162.00	63.7	14,210	1.482	8.8	4,815	16.42	6	35	54.98

(continued)

Table 2 (continued)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DS AHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD	Total water deficit DS AHD (BCM)
22	43A	RS. 20	160	590	161.27	64.3	14,110	1.436	8.7	4,507	19.69	5	40	42.93
23	44A	RS. 20	165	590	161.42	64.3	14,115	1.439	8.7	4,532	12.00	5	40	32.21
24	45A	RS. 20	170	590	161.43	64.1	14,466	1.521	8.7	4,784	15.07	5	35	31.64
25	46A	RS. 10	160	590	161.54	64.4	13,825	1.372	8.7	4,759	19.00	6	36	42.35
26	47A	RS. 10	165	590	161.69	64.3	13,962	1.403	8.8	4,845	15.43	6	35	36.94
27	48A	RS. 10	170	590	162.14	64.3	14,024	1.419	8.9	5,101	14.78	6	31	33.37

Table 3 The results of the primary indicators that represent the output results of the model for categories B (high flood)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DS AHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD hydropower	Total water deficit DS AHD (BCM)
1	10B	RS. 20	165	640	162.50	64.598	14,790	1.563	9.027	5,446	15.07	3	26	30.52
2	12B	RS. 20	170	640	162.77	64.590	14,789	1.562	9.140	5,499	15.91	3	26	31.05
3	11B	RS. 20	170	620	162.29	64.300	14,666	1.557	8.940	5,401	15.07	4	26	31.81
4	8B	RS. 20	160	640	162.14	64.587	14,789	1.562	8.880	5,351	15.06	4	27	33.09
5	9B	RS. 20	165	620	161.94	64.311	14,660	1.557	8.788	5,312	15.09	6	27	35.25
6	14B	RS. 10	160	640	162.80	64.759	14,477	1.495	9.063	5,687	15.11	4	22	37.46
7	43B	RS. 20	160	590	160.85	64.057	14,509	1.539	8.400	4,793	15.08	4	32	38.14
8	15B	RS. 10	165	620	162.47	64.464	14,321	1.483	8.937	5,621	15.10	4	22	38.17
9	44B	RS. 20	165	590	161.44	64.066	14,477	1.535	8.580	5,076	15.10	4	28	38.96
10	17B	RS. 10	170	620	162.98	64.454	14,326	1.485	9.133	5,738	12.71	4	22	39.03
11	16B	RS. 10	165	640	163.26	64.756	14,490	1.500	9.241	5,805	15.13	4	22	39.38
12	13B	RS. 10	160	620	162.10	64.470	14,324	1.484	8.798	5,454	15.11	4	24	39.94
13	48B	RS. 10	170	590	162.44	64.212	14,213	1.475	8.913	5,599	15.09	4	23	41.21
14	18B	RS. 10	170	640	163.58	64.745	14,497	1.502	9.370	5,880	15.18	4	21	41.60
15	7B	RS. 20	160	620	161.81	64.323	14,644	1.557	8.705	5,128	15.13	4	29	41.96
16	45B	RS. 20	170	590	162.14	64.075	14,499	1.544	8.816	5,334	15.14	4	26	42.00
17	47B	RS. 10	165	590	161.97	64.218	14,218	1.477	8.743	5,405	16.82	4	24	43.34
18	6B	EN. target	170	640	163.06	64.260	14,416	1.507	9.190	5,407	16.42	4	28	45.03
19	4B	EN. target	165	640	162.79	64.260	14,416	1.507	9.073	5,344	16.42	4	28	45.58
20	46B	RS. 10	160	590	161.58	64.224	14,217	1.478	8.613	5,170	16.50	3	27	45.97
21	2B	EN. target	160	640	162.42	64.260	14,416	1.507	8.924	5,225	16.42	4	28	46.84

(continued)

Table 3 (continued)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DS AHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD hydropower	Total water deficit DS AHD (BCM)
22	5B	EN. target	170	620	162.62	63.976	14,231	1.491	9.003	5,305	16.42	4	28	47.19
23	3B	EN. target	165	620	162.19	63.976	14,231	1.491	8.821	5,205	16.42	4	28	48.68
24	42B	EN. target	170	590	164.63	64.642	11,702	0.850	9.797	6,108	22.99	5	21	65.78
25	1B	EN. target	160	620	164.45	64.897	11,782	0.855	9.725	6,062	22.99	5	21	66.08
26	41B	EN. target	165	590	164.27	64.642	11,701	0.850	9.651	5,995	22.99	5	22	66.82
27	40B	EN. target	160	590	163.87	64.642	11,701	0.850	9.502	5,821	22.99	5	24	68.19

EN. target the policy used by Ethiopia to target the maximum energy produced from GERD, *RS. 20* a cooperative policy indicates keeping 20 BCM in GERD storage for the downstream use in drought periods, *RS. 10* A cooperative policy indicates keeping 10 BCM in GERD storage for the downstream use in drought periods

Table 4 The results of the primary indicators that represent the output results of the model for categories C (low flood)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DSAHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD hydropower	Total water deficit DS AHD (BCM)
1	12C	RS. 20	170	640	163.06	64.586	14,654	1.542	9.205	5,547	15.09	3	26	14.63
2	18C	RS. 10	170	640	163.41	64.738	14,413	1.480	9.337	5,880	16.61	2	21	16.00
3	10C	RS. 20	165	640	162.90	64.620	14,635	1.530	9.145	5,468	14.79	3	27	24.92
4	16C	RS. 10	165	640	163.21	64.760	14,404	1.476	9.274	5,834	14.79	3	22	27.22
5	11C	RS. 20	170	620	162.87	64.354	14,495	1.515	9.144	5,465	16.42	4	27	31.73
6	17C	RS. 10	170	620	163.36	64.533	14,150	1.430	9.301	5,770	14.88	5	23	32.86
7	4C	EN. target	165	640	162.94	64.344	14,510	1.527	9.139	5,322	19.63	3	29	33.57
8	8C	RS. 20	160	640	162.68	64.620	14,731	1.551	9.107	5,449	16.42	6	27	37.32
9	14C	RS. 10	160	640	163.22	64.798	14,375	1.470	9.261	5,756	16.42	4	23	38.34
10	45C	RS. 20	170	590	162.58	64.165	14,267	1.471	9.049	5,378	16.16	5	28	41.12
11	48C	RS. 10	170	590	162.97	64.319	13,949	1.394	9.177	5,667	16.59	5	24	41.92
12	2C	EN. target	160	640	162.69	64.344	14,510	1.527	9.066	5,197	21.93	4	30	42.47
13	9C	RS. 20	165	620	162.68	64.381	14,480	1.510	9.085	5,373	22.19	5	28	42.87
14	15C	RS. 10	165	620	163.00	64.520	14,228	1.444	9.211	5,730	22.29	4	23	44.92
15	5C	EN. target	170	620	163.12	64.087	14,298	1.486	9.211	5,402	22.99	4	28	46.64
16	6C	EN. target	170	640	163.12	64.087	14,298	1.486	9.211	5,402	23.68	4	28	46.64
17	7C	RS. 20	160	620	162.40	64.381	14,443	1.498	9.011	5,271	22.99	7	29	51.64
18	13C	RS. 10	160	620	162.87	64.561	14,110	1.417	9.159	5,562	22.24	7	25	51.90
19	3C	EN. target	165	620	162.87	64.087	14,298	1.486	9.128	5,328	22.99	4	29	58.14
20	44C	RS. 20	165	590	162.53	64.180	14,326	1.479	9.043	5,293	22.99	7	29	58.70
21	47C	RS. 10	165	590	162.97	64.337	14,029	1.408	9.186	5,592	15.09	7	25	60.73

(continued)

Table 4 (continued)

No.	Scenario	Operating rule	Initial AHD level (masl)	Initial GERD level (masl)	Average AHD level (masl)	Average inflow AHD (BCM)	GERD annual energy (GWh)	GERD annual evaporation (BCM)	AHD annual evaporation (BCM)	AHD energy (GWh)	Max water deficit DSAHD (BCM)	NO of water deficit DS AHD	NO of shutdown AHD hydropower	Total water deficit DS AHD (BCM)
22	42C	EN. target	170	590	162.82	63.832	14,223	1.482	9.114	5,313	16.61	5	29	62.54
23	43C	RS. 20	160	590	162.15	64.183	14,229	1.460	8.938	5,212	14.79	7	30	64.16
24	1C	EN. target	160	620	162.67	64.087	14,298	1.486	9.067	5,254	14.79	5	30	68.23
25	46C	RS. 10	160	590	162.69	64.340	13,989	1.397	9.110	5,538	16.42	7	26	69.07
26	41C	EN. target	165	590	162.60	63.832	14,223	1.482	9.046	5,200	14.88	6	30	75.43
27	40C	EN. target	160	590	162.41	63.832	14,223	1.482	8.997	5,097	19.63	6	32	86.81

cause negative impacts on the energy sector of the AHD. Cooperative regulation policies are also shown to benefit the Ethiopian energy sector over and above the Ethiopian regulation policy. The main indicators that are selected to address the results of the model are as follows:

1. Average annual level of AHD (m)
2. Average annual water inflow at AHD (BCM)
3. Average annual energy production of GERD (GWH/year)
4. Average annual evaporation of GERD (BCM)
5. Average annual evaporation of AHD (BCM)
6. Average annual energy production (AHD + OAD) (GWH/year)
7. Maximum water deficit DS AHD
8. Number of water deficit DS AHD
9. Number of shutdown years of AHD (years)
10. Total water deficit DS AHD (BCM)

These indicators have been given in the previous tables and are shown in the following curves to get a clear summary of the results of different scenarios. The initial levels of GERD and AHD were used to describe the situation of the system when the operation starts. Since we are not considering filling in this study, we assume that the simulated operation occurs after filling. Therefore, we proposed some initial AHD levels that might exist when operating GERD. We know from previous studies that AHD will empty as GERD fills, but the current study does not exactly calculate post-filling levels, since that depends on a number of factors, including Blue Nile flow during the filling period, the length of the filling period, etc.

That is why the AHD was selected to check for 160, 165, and 170 masl as initial levels. On the other hand, different initial levels were selected to check for GERD as 590, 620, and 622 masl.

It should be noted that the maximum storage level of GERD (640 m) was not considered as initial level in the analysis of selecting the best regulation policies of GERD. It is not expected that GERD will reach that level at the end of the filling period where the dam is supposed to be operated and release water during the filling period. The best operating policies, therefore, will be selected for each initial level of GERD and the selected three initial levels of AHD.

6.2 Best Regulation Policies Under Category A (Normal Flood)

The following curves show the different outputs resulting from the model under the category (A). Figures 6 and 7 show the average annual levels and the average 10-day levels for both GERD and AHD, respectively, for all 27 policies. Figure 8, on the other hand, shows the water deficit downstream AHD.

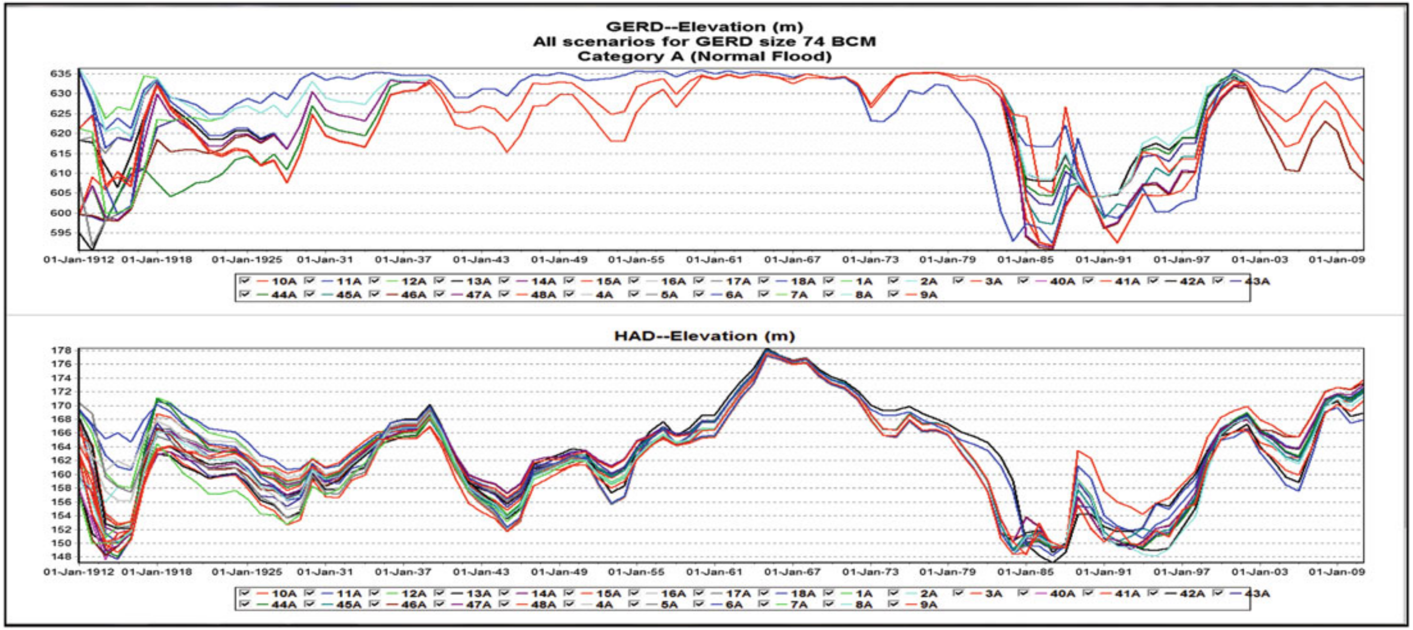


Fig. 6 Average annual levels of GERD and AHD for category A

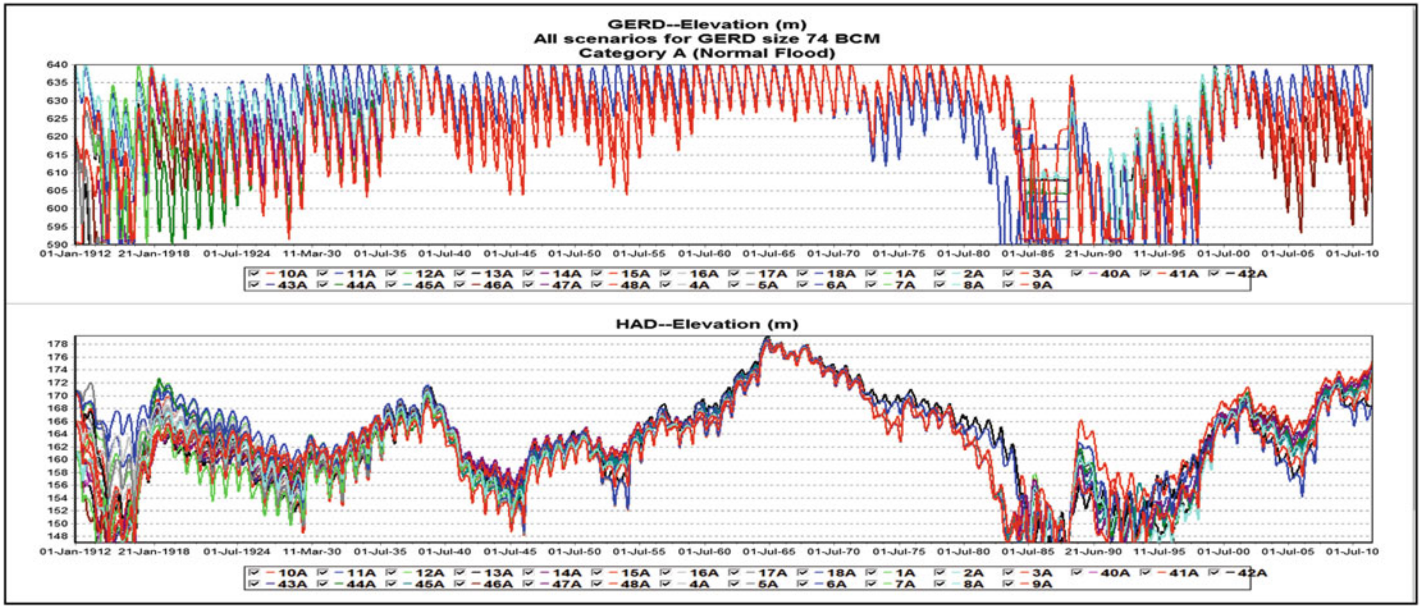


Fig. 7 Average 10-day levels of GERD and AHD for category A

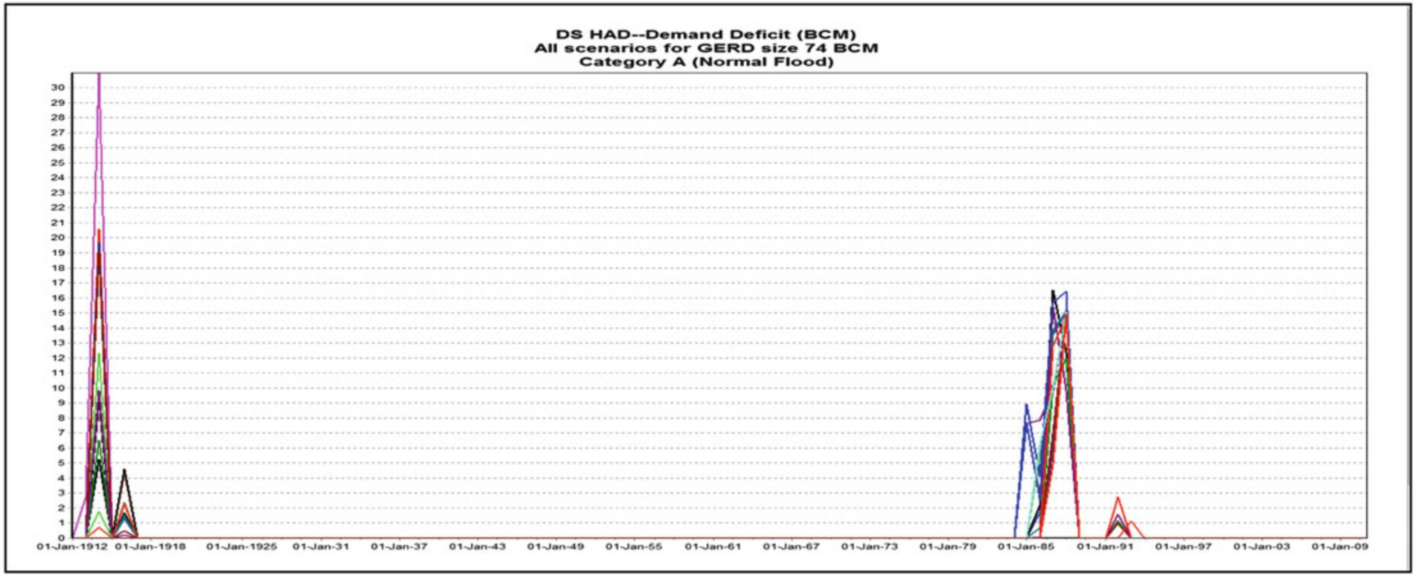


Fig. 8 Water deficit downstream AHD for category A

The results shown in Table 2 for GERD storage 74 BCM will easily lead to the selection of the best regulation policy for GERD out of the three studied policies (Energy target, 20 BCM reserve or 10 BCM reserve), depending on the selection criteria.

The main two factors that affect the management of the AHD due to the regulation policy of GERD are the annual total water deficit downstream AHD and the generated energy from AHD. Those two evaluating factors have been taken for this study as the most critical criteria for arranging and selecting the best policies among the scenarios incorporated into the model.

Other criteria for comparison and selection of the best policies could be the number of shutdowns of AHD hydropower production or the value of the maximum water deficit occurred downstream AHD.

The output results shown in Table 2 were rearranged according to the evaluating factors, the initial levels of both GERD and AHD to identify the best operating policy in each case that satisfies the above two conditions. Table 5 describes the best policies for regulating GERD with minimum impacts on AHD in terms of water deficit in the downstream. On the other hand, Table 6 illustrates the same as the main criterion of achieving maximum power production from AHD.

Table 5 Results of energy-target policy for category A (normal flood)

HAD initial level (m)	GERD initial level (m)	Policy number	Policy description
160	590	40A	HAD total water deficit = 83.45 BCM Max water deficit DS HAD = 31 BCM GERD energy = 14,209.76 GWH HAD energy = 7,822 GWH
160	620	1A	HAD total water deficit = 62.06 BCM Max water deficit DS HAD = 16.42 BCM GERD energy = 14,285.42 GWH HAD energy = 7,441 GWH
165	590	41A	HAD total water deficit = 70.33 BCM Max water deficit DS HAD = 20.58 BCM GERD energy = 14,209.76 GWH HAD energy = 7,914 GWH
165	620	3A	HAD total water deficit = 49.60 BCM Max water deficit DS HAD = 16.42 BCM GERD energy = 14,285.42 GWH HAD energy = 7,499 GWH
170	590	42A	HAD total water deficit = 54.98 BCM Max water deficit DS HAD = 16.42 BCM GERD energy = 14,209.76 GWH HAD energy = 7,968 GWH
170	620	5A	HAD total water deficit = 45.14 BCM Max water deficit DS HAD = 16.42 BCM GERD energy = 14,285.42 GWH HAD energy = 7,729 GWH

Table 6 Results of 20 BCM reserve policy for category A (normal flood)

HAD initial level (m)	GERD initial level (m)	Policy number	Policy description
160	590	43A	HAD total water deficit = 42.93 BCM Max water deficit DS HAD = 19.69 BCM GERD energy = 14,109.84 GWH HAD energy = 8,016 GWH
160	620	7A	HAD total water deficit = 22.72 BCM Max water deficit DS HAD = 14.85 BCM GERD energy = 14,306.05 GWH HAD energy = 7,145 GWH
165	590	44A	HAD total water deficit = 32.21 BCM Max water deficit DS HAD = 12.0 BCM GERD energy = 14,114.69 GWH HAD energy = 8,247 GWH
165	620	9A	HAD total water deficit = 21.00 BCM Max water deficit DS HAD = 14.91 BCM GERD energy = 14,151.13 GWH HAD energy = 7,700 GWH
170	590	45A	HAD total water deficit = 31.64 BCM Max water deficit DS HAD = 15.07 BCM GERD energy = 14,465.72 GWH HAD energy = 8,342 GWH
170	620	11A	HAD total water deficit = 30.25 BCM Max water deficit DS HAD = 14.85 BCM GERD energy = 14,629.07 GWH HAD energy = 7,931 GWH

6.2.1 Results of Energy-Target Regulation Policy

The output results shown in Table 2 were rearranged according to the three main policies (energy target, 20 BCM reserve, 10 BCM reserve) and the evaluating factors, the initial levels of both GERD and AHD to identify the best operating policy in each case that satisfies the above two conditions. Table 5 illustrates the results of the model for the energy-target regulating policy of GERD indicating the total water deficit in the downstream, the maximum value of this deficit, the GERD energy, and the AHD and OAD energy.

6.2.2 Results of 20 BCM Reserve Regulation Policy

Table 6 illustrates the results of the model for the 20 BCM reserve regulating policy of GERD indicating the total water deficit in the downstream, the maximum value of this deficit, the GERD energy, and the AHD energy.

6.2.3 Results of 10 BCM Reserve Regulation Policy

Table 7 illustrates the results of the model for the 10 BCM reserve regulating policy of GERD indicating the total water deficit in the downstream, the maximum value of this deficit, the GERD energy, and the AHD energy. The same analysis was done for the other two categories B and C. The best regulation policy for GERD was selected depending on the same selection criteria. Tables 8, 9, and 10 summarize the results obtained for this study.

Table 7 Results of 10 BCM reserve policy for category A (normal flood)

HAD initial level (m)	GERD initial level (m)	Policy number	Policy description
160	590	46A	HAD total water deficit = 42.35 BCM Max water deficit DS HAD = 19.0 BCM GERD energy = 13,825.43 GWH HAD energy = 8,073 GWH
160	620	13A	HAD total water deficit = 41.90 BCM Max water deficit DS HAD = 16.52 BCM GERD energy = 14,281.17 GWH HAD energy = 7,794 GWH
165	590	47A	HAD total water deficit = 36.94 BCM Max water deficit DS HAD = 15.43 BCM GERD energy = 13,961.93 GWH HAD energy = 8,167 GWH
165	620	15A	HAD total water deficit = 22.97 BCM Max water deficit DS HAD = 14.92 BCM GERD energy = 13,957.01 GWH HAD energy = 7,913 GWH
170	590	48A	HAD total water deficit = 33.37 BCM Max water deficit DS HAD = 14.78 BCM GERD energy = 14,023.72 GWH HAD energy = 8,708 GWH
170	620	17A	HAD total water deficit = 39.45 BCM Max water deficit DS HAD = 15.13 BCM GERD energy = 14,311.34 GWH HAD energy = 8,246 GWH

Table 8 Water deficit downstream HAD in normal flood

HAD level (m)	GERD level (m)	Water deficit DS HAD (BCM)		
		Rule of energy target	Rule of 20 BCM reserve	Rule of 10 BCM reserve
160	590	83.45	42.93	42.35
160	620	62.06	22.72	41.90
165	590	70.33	32.21	36.94
165	620	49.60	21.00	22.97
170	590	54.98	31.64	33.37
170	620	45.14	30.25	39.45

Table 9 Energy production from GERD in normal flood

HAD level (m)	GERD level (m)	Energy of GERD (GWH)		
		Rule of energy target	Rule of 20 BCM reserve	Rule of 10 BCM reserve
160	590	14,209.76	14,109.84	13,825.43
160	620	14,285.42	14,306.05	14,281.17
165	590	14,209.76	14,114.69	13,961.93
165	620	14,285.42	14,151.13	13,957.01
170	590	14,209.76	14,465.72	14,023.72
170	620	14,285.42	14,629.07	14,311.34

Table 10 Energy production from HAD and OAD in normal flood

HAD level (m)	GERD level (m)	Energy of HAD + OAD (GWH)		
		Rule of energy target	Rule of 20 BCM reserve	Rule of 10 BCM reserve
160	590	7,822	8,016	8,073
160	620	7,441	7,145	7,794
165	590	7,914	8,247	8,167
165	620	7,499	7,700	7,913
170	590	7,968	8,342	8,708
170	620	7,729	7,931	8,246

6.3 *Best Regulation Policies Under Categories B and C*

The same analysis was done for the other two categories B and C, and the results were represented by the same graphs and tables. The best regulation policies for GERD were selected depending on the same selection criteria. Table 7 summarizes the results obtained for this study. The operating policies shown in the table are selected as the best policies that could be used for GERD according to the criteria of minimum water deficit downstream AHD. On the other hand, Table 8 summarizes the best results obtained from the three categories according to the criteria of achieving maximum energy production from AHD.

The present results shown in Tables 5, 6, and 7 indicate the following:

1. In case of using the policy of keeping a reserve of 20 BCM of GERD live storage for the use of the downstream countries, when needed, it is noted that a minimum water deficit downstream AHD is achieved in scenario 9A, if the operation started. This was achieved under the conditions that the initial level of GERD is 620 m and the water level of AHD is 165 m. The total water deficit downstream AHD along the 100-year period tested by the model is 21.0 BCM distributed over 3 years with a maximum value of 14.91 BCM. The number of shutdowns of the turbines of AHD during the 100-year period will reach 31 times where AHD fails to produce power. The energy produced from GERD is 14,151.13 GWH.

2. In case of using the policy of keeping a reserve of 10 BCM of GERD live storage for the use of the downstream countries when needed, it is noted that a minimum water deficit downstream AHD is achieved in scenario 15A if the operation started. This was achieved when the initial level of GERD is 620 m and the water level of AHD is 165 m. The total water deficit downstream AHD along the 100-year period tested by the model is 22.97 BCM distributed over 3 years with a maximum value of 14.92 BCM. The number of shutdowns of the turbines of AHD during the 100-year period will reach 28 times where AHD fails to produce power. The energy produced from GERD is 13,957.01 GWH.
3. In case of using the policy of energy target, it is noted that a minimum water deficit downstream AHD is achieved in scenario 5A if the operation started when the initial level of GERD is 620 m and the water level of AHD is 170 m. The total water deficit downstream AHD along the 100-year period tested by the model is 45.14 BCM distributed over 3 years with a maximum value of 16.42 BCM. The number of shutdowns of the turbines of AHD during the 100-year period will reach 32 times where AHD fails to produce power. The energy produced from GERD is 14,285.42 GWH.
4. From the above, it is quite clear that the cooperative operation rule with 20 BCM reserve in GERD storage is the best policy for the reduction of water deficit DS AHD and at the same time gives reasonable hydropower energy from GERD compared with the energy target operating rule. It is also noted that using the energy target policy produces hydropower energy from GERD equal to 14,285.42 GWH compared with 14,151.13 GWH produced when using the cooperative policy with 20 BCM reserve in GERD storage, i.e., the power production increase is less than 1%.

7 Conclusions

It is quite clear from the previous analysis that the best regulation policies depend mainly on the operating rule of the dam and the initial levels of GERD and AHD. For each initial level of AHD, three different operating rules for GERD were compared. The first rule is the Ethiopian policy of maximizing the produced energy (energy target, EN target), the second rule is the cooperative regulation policy which requires maintaining a reserve of 20 BCM, and the third rule is the cooperative regulation policy that requires maintaining a reserve of 10 BCM.

The cooperative management of GERD proved to be the most dominant factor that affects the selection of the best operating policy. Keeping a specific storage reserve in GERD for the use of the downstream countries in drought years affects positively the impacts on AHD in terms of water deficit and power generation shortage. The difference between the cooperative policy and the energy target policy of GERD (noncooperative) is significant in terms of the quantity of water deficit downstream AHD. For the same initial level of GERD, it is found that the higher water level of AHD at the beginning of the operation, the lower the total water deficit downstream AHD.

The following can be concluded from this study:

1. GERD with its current storage capacity of 74 BCM reduces the ability of the Aswan High Dam as a long-term storage reservoir as indicated by the increase in water deficit quantity and frequency.
2. As currently proposed by Ethiopia, the GERD project and associated regulation rules will inflict much higher risks of water deficit downstream AHD and power reduction/shutdown on Egypt.
3. The storage capacity of the GERD in light of the negative impacts which is not reflected in the same magnitude as in increasing the power generation for Ethiopia. Therefore, a dam of a smaller size would have been more efficient and cost-effective.
4. The best regulation policies depend mainly on the operating rule of the dam and the initial levels of GERD and AHD.
5. The difference between the cooperative policy and the energy target policy of GERD (noncooperative) is significant in terms of the quantity of water deficit downstream AHD.
6. The cooperative management of GERD proved to be the most dominant factor that affects the selection of the best operating policy. Keeping storage reserve in GERD (20 BCM) for the use of the downstream countries in drought years affects positively the impacts on AHD in terms of water deficit and power generation shortage.

8 Recommendations

1. The operation of GERD should be linked to the operation of AHD.
2. Best operating policies of GERD should consider reserve storage for downstream countries.
3. Selection of best operating policy of GERD should be based on the minimum water deficit downstream AHD.
4. The capability of Nile conservation projects to balance the amount of water reduction associated with development in the Blue Nile should be studied. Full benefits and mitigation of their impacts should be thoroughly investigated.
5. The efficiency of the GERD and Border Dam needs to be studied using sound economic analysis, in light of the high cost of GERD and the low efficiency in comparison with the low cost of Border Dam and high efficiency of power generation.
6. The potential influence of climate changes on the flow regime at the GERD and further downstream needs to be investigated.
7. Other provisions for drought management in GERD operation should be thoroughly studied. Downstream socioeconomic, as well as environmental, impacts should also be considered in developing such operation policies.

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GERD Failure Analysis and the Impacts on Downstream Countries

Ahmed H. Soliman, Alaa El Zawahry, and Hesham Bekhit

Contents

Abstract The Grand Ethiopian Renaissance Dam (GERD) is one of the major dams under construction on the Nile River. Currently, there is a lot of confusion about the impacts of GERD on downstream countries (Sudan and Egypt). One of the major impacts on downstream countries that has attracted a lot of debate is the impact of GERD failure. This paper aims to investigate the impacts of GERD failure in downstream regions using the International River Interface Cooperative (IRIC) two-dimensional analysis model. The study reveals that there could be a catastrophic effect on Sudan especially Roseires, Sennar, and Merowe dams in addition to Al Khartoum City. Also, the study shows that the Aswan High Dam (AHD) will be at risk.

Keywords Aswan High Dam, Dam failure, GERD, Impacts, Modeling, Nile River

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1 Introduction

On 31 March 2011, a US$4.8 billion contract was awarded to Salini Costruttori to build a dam named "Project X" which was classified as the largest dam on the Blue Nile River. Construction was announced unilaterally by the Ethiopian Ministry of Water Resources and Energy. Ethiopia's Prime Minister laid the dam's foundational stone on 2 April 2011 [1]. The dam's name was changed to the "Millennium Dam" with a capacity volume of 63 BCM. The Ethiopian Ministers Council renamed the dam again on 15 April 2011 to the "Grand Ethiopian Renaissance Dam (GERD)" which would stand 145 m high with a total volume of 74 BCM (dead and live storage).

The GERD is located to the east of the borderline between Ethiopia and Sudan on the Blue Nile as shown in Fig. 1. The GERD is designed with a dead storage of about 14 BCM, which corresponds to a depth of 90 m measured from the reservoir bed level. GERD layout consists of main and saddle dams (Fig. 1). The main dam is designed to be a roller-compacted concrete (RCC) dam, while the saddle dam is a traditional embankment dam. The saddle dam is about 55 m high which will retain about 60 BCM of water. Based on the International Commission on Large Dams (ICOLD), the main and saddle dams are classified as large dams [2] because their heights are greater than 15 m and their storage volumes are more than one million cubic meters. After the completion of GERD, it will be classified as the fourth highest dam in Africa [3].

Hydropower generation is the main purpose of GERD, but it is expected to have several impacts on the downstream regions. One of the major impacts is the impact of the surge wave generated due to dam failure or generated in case of rapid dam evacuation due to any unforeseen circumstances. The surge wave depth to be expected due to dam break is compared with the total dam height and traveling at very high speed. Accordingly, very devastating impacts may occur in the downstream developed areas. Such damaging force can cause fatalities especially if there is no early warning and no emergency evacuation plans. In general, flood waves resulting from typical dam breaks have been responsible for numerous losses to the nearby community. Therefore, it is highly important to investigate the different what-if scenarios related to the break of the dam due to any unexpected circumstances. The carrying out of a dam break analysis is mandatory based on the recommendation of the ICOLD. The scope of such analysis is to investigate the motion of the produced positive surge wave downstream of the dam site, and this is typically carried out using a fully dynamic dam break analysis.

Failures of dams and water retaining structures continue to occur, even with the advancements in design methodologies. Several dam failures occurred in the mid-1970s, including Buffalo Creek coal waste dam (West Virginia, 1972), Teton Dam (Idaho, 1976), Laurel Run Dam and Sandy Run Dam (Pennsylvania, 1977), Canyon Lake Dam (South Dakota, 1972), Kelly Barnes Dam (Georgia, 1977), and Lawn Lake Dam (Colorado, 1982). Each of these dam failures resulted in catastrophic damages of property and human death. To give few examples, failure of

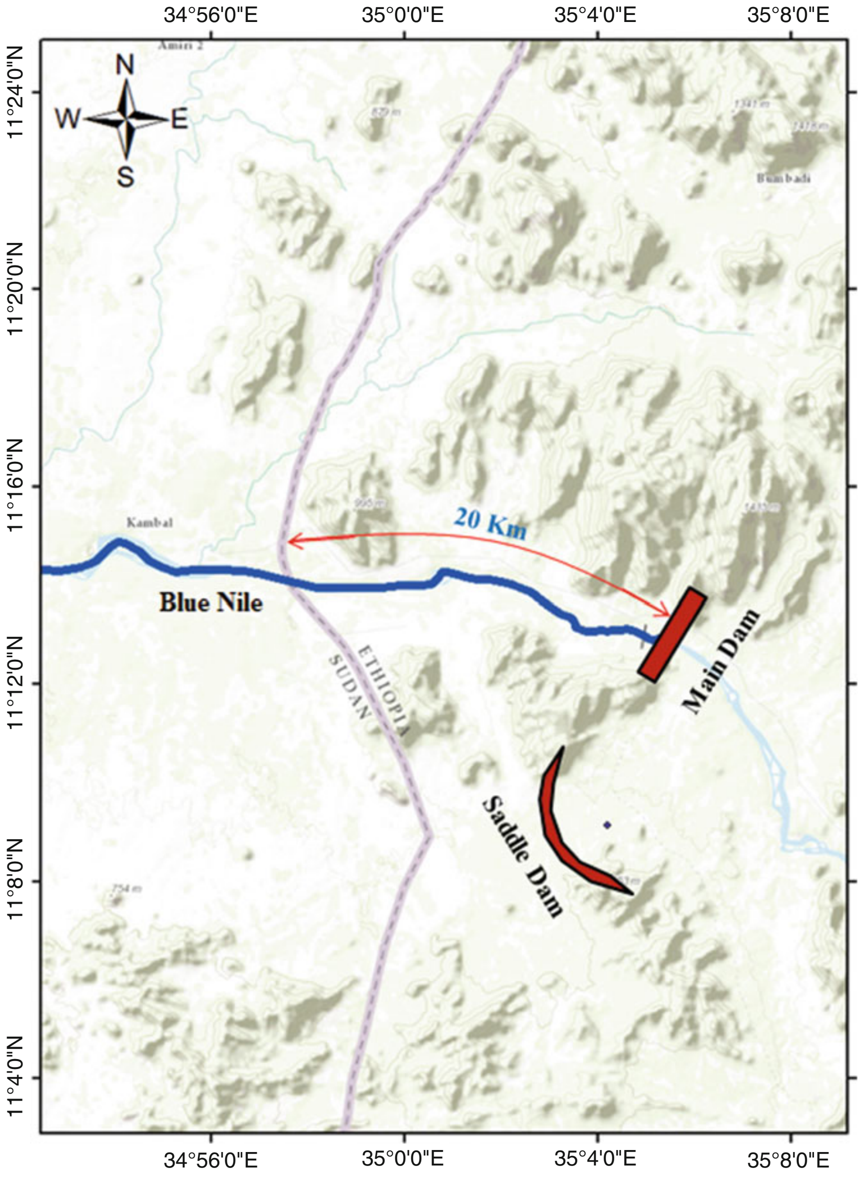

Fig. 1 Location of GERD

the Malpasset Concrete Dam in France in 1959 caused 433 casualties. Two thousand people died in Italy when a landslide occurred on the Vajont reservoir, which caused a flood wave more than 100 m high that overtopped the dam and flooded the downstream valley. In July 1985, a Stave Dam in Italy failed, and about 90% of the 300 people living in Stava near the Stave Dam also died. More recently, in May

1999 in Southern Germany, a dam failed and caused four deaths and over one billion Euros of damage. In Spain in 1997, failure of a dam on the Guadalquivir River caused immense ecological damage due to the release of polluted sediments in the river valley. Last, but not the least, in Romania, failure of a mine tailings dam released lethal quantities of cyanide in the river system, polluting the environment and a major source of drinking water for both Romania and Hungary.

In the case of GERD, the dam break analysis is very crucial due to the huge size and large dimensions of the dam. In addition to the high risk of soil instability in the site location which leads to a high probability of failure associated with GERD. GERD is located on one of the major tectonic plates and faults in the world. Around that fault, about 15,000 earthquakes are documented in Ethiopia [4]. During the twentieth century, about 16 earthquakes with a magnitude higher than or equal to 6.5 occurred in Ethiopia at the fault which causes severe damages [5, 6].

Among other factors that necessitate the analysis of the dam break is the current condition downstream of the dam site. Several dams and cities are located downstream GERD. Five dams downstream GERD would be affected by the dam failure, three of these dams are located within Sudan boundaries (i.e., Roseires, Sennar, and Merowe), while the remaining two dams are located inside Egypt (i.e., Aswan High Dam and Aswan Reservoir). Several small to large cities in Sudan are located just downstream of GERD which includes Sudan's capital city – Al Khartoum.

Therefore, the main objective of this paper is to investigate and analyze the effect of GERD main dam failure on the downstream region. The analysis will include assessing the risk associated with the downstream region up to Aswan High Dam due to GERD main dam failure.

To achieve this objective, dam break simulation is required. As the extreme nature of dam break floods will alter the flow conditions, which will exceed by far the magnitude of most natural flood events. Under these conditions, the flow will behave differently which makes dam break analysis a mandatory study for the risk management and disaster management plan. Therefore, the analysis scope will be the flood routing and simulation of the movement of the GERD dam break flood wave along the river particularly any area downstream the GERD that would be affected by its failure. The International River Interface Cooperative (IRIC) software developed by a cooperation between US Geological Survey (USGS), the universities of Hokkaido and Kyoto, Mizuho Corporation, and the Foundation of the River Disaster Prevention Research Institute in Sapporo, Japan [7], is used to simulate the failure of the GERD main dam in addition to the downstream hydraulic properties of the generated surge wave. NAYS2D Flood solver was selected to be used to simulate the effect of the surge wave due to GERD failure in the downstream region. IRIC investigates the impact of a dam failure at any point of interest downstream the dam in terms of:

- Time of the first arrival of flood water
- Peak water level and time of peak
- Extent of inundation

- Depth and velocity of flood water
- Duration of the flood

Digital elevation model (DEM) with 90 m resolution was used to generate the geometric data required for hydraulic simulation. Although DEM data with different resolutions may have concerns on their accuracies, DEM accuracy will not significantly affect dam break simulation due to a large amount of water released due to dam failure [8].

2 Hydraulic Simulation Methodology

The methodology applied to this study is presented in Fig. 2.

As shown in Fig. 2, the methodology starts with obtaining the required topographical data for the study area and ends with the production of flood flow properties. At the beginning, the IRIC model is built using the digital elevation model (DEM) and/or actual survey. Meanwhile, the study area is divided into several simulation reaches which were selected based on the topography and control sections. Once the IRIC project is built, the calibration process starts. The calibration is an ongoing process between IRIC and the calibration data (discharge, water depth, flow velocity, and the corresponding Manning's coefficient(s)). After the calibration of the built simulation, the dam characteristics are inserted into a code developed to calculate the required breach opening dimensions and formation time for the considered dam in the simulated reach which are calculated using Soliman equations [9, 10]. After that, the calculated breach parameters, in addition to the inflow hydrograph to the dam reservoir, are used to calculate the effect of reservoir routing and the outflow hydrograph due to dam failure. Knowing the outflow hydrograph due to dam failure, the hydraulic simulation using IRIC was used to calculate flow properties along the simulated reach. Finally, the simulation outputs are presented as the hydraulic properties of the outflow hydrograph at different locations along the simulation reaches.

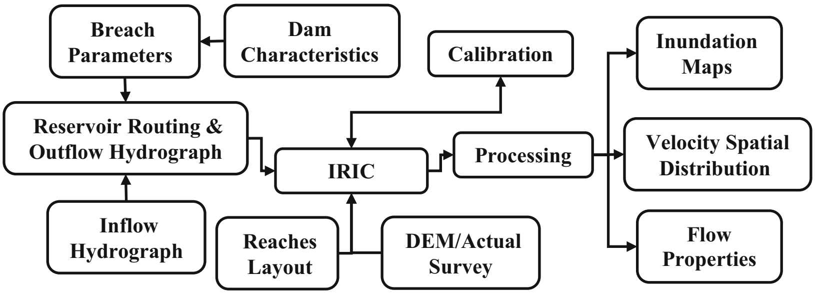

Fig. 2 Methodology applied to the two-dimensional simulation

3 Hydraulic Simulation Reaches

The study area was divided into several reaches based on the location of the existing structures in addition to river topography. There are five dams along the study area (GERD to AHD). Three of them are located along the Blue Nile (GERD, Roseires, and Sennar). The remaining two dams (Merowe and AHD) are located along the main Nile River after the confluence of the Blue Nile and White Nile near Al Khartoum. There are at least four reaches to connect the five dams. The junction between the Blue Nile and White Nile is located at Al Khartoum. It is downstream of Sennar Dam and upstream of Merowe Dam. In addition to the contraction area just downstream of Al Khartoum, the reach between Sennar and Merowe dams was divided into three reaches. Accordingly, the study area was divided into six reaches as presented in Fig. 3.

The six reaches started from GERD at the upstream and ended at AHD at the downstream as presented in Fig. 3.

As shown in Fig. 3, the first reach is between GERD and the entrance of Roseires Dam reservoir. This reach is controlled at the upstream by GERD which is characterized by 74 BCM storage volume and 145 m height.

The second reach is between Roseires Dam and the entrance of Sennar Dam reservoir. The second reach is upstream and controlled by Roseires Dam which is located on the Blue Nile at Ad Damazin City. The Roseires Dam is a concrete dam built in 1966 and heightened in 2013. The dam initial capacity was 3.0 BCM which was upgraded to be 7.8 BCM in 2013. The final dam height is 78 m with the length of 24 km. Roseires Dam has two main functions. The first function is to provide the required irrigation water to the surrounding agriculture land. The second function is to supply hydropower generation as the installed power of Roseires Dam is 280 MW [11].

The third reach is between the Sennar Dam and Al Khartoum City. The Sennar Dam is the control structure at the upstream end of the third reach which is located at the Blue Nile at Sennar City. It is a rockfill dam built in 1926. The Sennar Dam is about 40 m high and 3 km long and has a reservoir capacity of 0.83 BCM. It provides irrigation water to several agriculture projects such as Al-Rahad and Al-Soky projects [12]. Also, the Sennar Dam is used in hydropower generation as it has an installed capacity of 15 MW [11].

The fourth reach is between Al Khartoum City and the contraction area which is located at Abu Dawm and Al Huqnah regions. The fifth reach is between the contraction area and the entrance of the Merowe Dam reservoir. At the downstream of this reach, the Merowe Dam exists which is located on the Nile River near Merowe City. Merowe Dam is classified as one of the large dams on Nile River and was built in 2009. It is an embankment dam with a concrete spillway. Merowe Dam is about 67 m high and 9 km long with 12.4 BCM storage capacity. The reservoir length is about 174 km, while its area is about 780 km^2. The main objective of Merowe Dam is hydropower generation as it has an installed capacity of 1,250 MW [13].

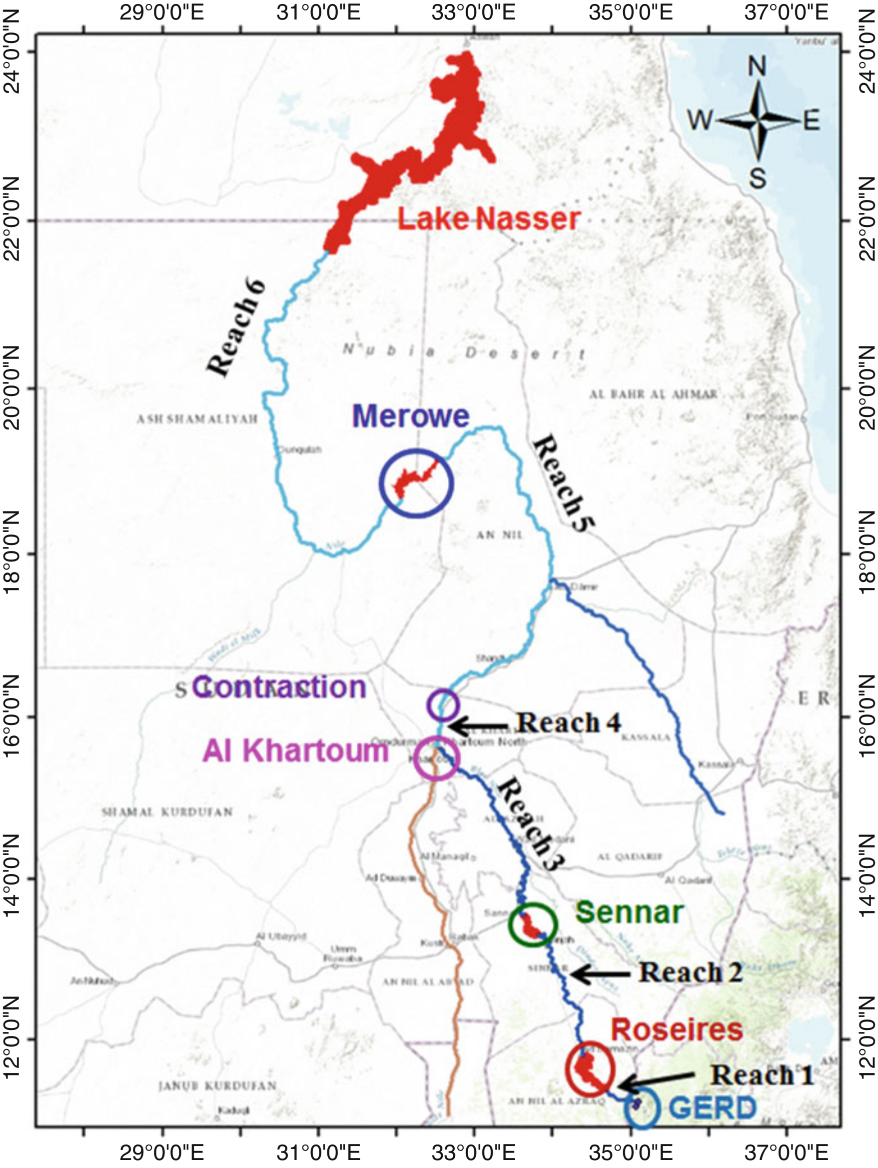

Fig. 3 Layout of simulation reaches

The last reach is between Merowe Dam and the entrance of Lake Nasser (Aswan High Dam (AHD) Reservoir). The AHD is located on the Nile River in the Aswan district. It is one of the major structures in Africa. The AHD was built in 1971 and is a rockfill dam with clay core. The dam height is about 111 m, and it retains about 162 BCM at water level equal to 182 m which is described as the maximum

Table 1 Lengths of the simulated reaches

Reach #	From	To	Length (km)
1	GERD	Roseires Dam	123
2	Roseires Dam	Sennar Dam	297
3	Sennar Dam	Al Khartoum City	389
4	Al Khartoum City	Contraction area	97
5	Contraction area	Merowe Dam	676
6	Merowe Dam	Lake Nasser	1,088
Total length			2,670

allowable water level. The dead storage is about 32 BCM where the live storage is about 90 BCM. The remaining 40 BCM is emergency storage [14]. In 1982, an emergency spillway was built at Toshka [15]. To the downstream of the emergency spillway, a channel was built to deliver the spilled water to the Toshka depression. One of the main purposes of the AHD in addition to flood protection, irrigation, and municipal use is hydropower generation. The AHD has an installed capacity of 2,100 MW.

After the application of the abovementioned methodology and taking the six reaches into consideration, the IRIC simulation was developed. The developed IRIC simulation was composed of six separate simulations (one per reach). The total length of the developed simulation was about 2,670 km. The length of each reach is presented in Table 1.

As shown in Table 1, the reach length varies between 97 and 1,088 km. The longest reach is number 6 while the shortest reach is number 4. The reach lengths presented in Table 1 are measured from the location of the upstream control structure to the downstream control structure or city including the reservoir length if it exists along the reach. Thus, for reaches 1, 2, 5, and 6, the simulation lengths using IRIC will be less than those mentioned in Table 1, while for reaches 3 and 4, it will be equal to that mentioned in the same table. Now, the IRIC simulation is conducted and ready for calibration to adjust simulation parameters. Also, the boundary conditions of each reach are the upstream flow hydrograph and the downstream reservoir properties.

4 Calibration of Hydraulic Simulation

Calibration is the process of modifying the input parameters to a hydraulic model until the output from the model matches an observed set of data. The main objective of IRIC simulation calibration is to find the best values of simulation parameters that affect the simulation results. The most important and effective parameter in the hydraulic modeling is roughness coefficient. IRIC uses Manning's formula to simulate the roughness. Therefore, the calibration process is concentrated on Manning's coefficient (n). As the rivers' cross sections will not accommodate the expected flood water due to GERD failure, Manning's coefficients at floodplains in addition to its value at deep channel are required. In this study, an effort has been made to calibrate Manning's roughness coefficient for both deep channel and floodplain. The data pertaining to the actual measurements of hydraulic properties at several locations have been used for calibration of Manning's roughness coefficient, *n*. Actual measurements include flow velocity, water depth, flow area, and the corresponding discharge.

Four flow gauges with discharge readings were available for this study. Two gauges were located on the Blue Nile (Roseires and Sennar gauges) while the other two gauges were located along the main Nile River (Tamaniat and Hudieba gauges).

IRIC simulation was used to conduct a steady state flow simulation to select the best combination of Manning's coefficients at each river section and along the river. A range of Manning's coefficient values between 0.01 and 0.10 were used to conduct the steady-state IRIC simulation. The root sum squared error (RSSE) test was used to select the best Manning's coefficient at each flow station. The calculated RSSE for observed and simulated velocities corresponding to each Manning's coefficient value at each flow station is presented in Fig. 4.

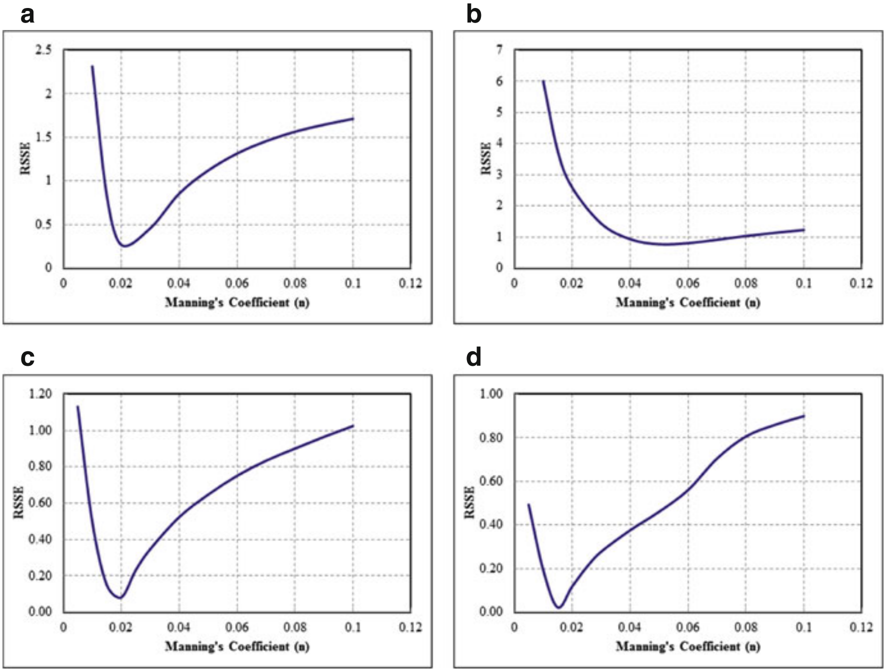

Fig. 4 RSSE in velocity at each flow gauge. (**a**) Roseires gauge. (**b**) Sennar gauge. (**c**) Tamaniat gauge. (**d**) Hudieba gauge

As can be concluded from Fig. 4, the minimum RSSE at Roseires station corresponds to Manning's coefficient equal to 0.022, while for Sennar station, it corresponds to 0.050. Also, the minimum RSSE at Tamaniat station was found at 0.020 Manning's coefficient, while it was at 0.015 for Hudieba station.

The calibration of floodplain Manning's coefficient was not as easy as the deep channel one. This is due to the absence of a historical record which has high discharge value (may exceed one million cubic meters per second) as expected from GERD failure. Accordingly, the evaluation of Manning's coefficients at floodplains in this study depends on land use, soil type, and literature values of Manning's coefficients.

Using satellite images and geological maps in addition to Manning's values recommended by Chow [16], Manning's coefficients for floodplains were estimated. The estimated Manning's coefficients reached 0.10.

5 Hydraulic Simulation Results and Discussions

After the calibration process, IRIC simulation is capable of simulating the target event. The simulation of the six reaches is conducted sequentially (i.e., reaches 1–6). The simulation of reach 1 is conducted to calculate the outflow hydrograph due to GERD failure and its hydraulic properties. The objective of the simulation of other reaches is to check the effect of GERD failure on the existing dams, agriculture land, and residential areas.

As mentioned earlier, the first reach started at GERD and ended at the entrance of Roseires reservoir. GERD is about 145 m high and has a storage capacity about 74 BCM. Using the dam characteristics, the breach opening dimensions are calculated and found to be 750 m for average breach width, 123 m for depth to final breach elevation, and about 6.7 h for the formation time. The first reach was simulated on IRIC model using grid size 500 m in river direction and 200 m perpendicular to river direction. The selected grid covers about 4,312 km^2. The inflow and outflow hydrographs of the first reach are presented in Fig. 5.

As shown in Fig. 5, the peak discharge at GERD due to its failure is about two million cubic meters per second and occurred after 5 h from the beginning of GERD main dam failure. The outflow volume is found to be 72.90 BCM which represents about 98.5% of GERD capacity. Additionally, the outflow hydrograph at the downstream section of the first reach as presented in Fig. 5 shows the peak flow as 1,310,000 m^3/s, and it reached after 11 h from the beginning of GERD main dam failure. The water volume at the entrance of Roseires Dam is 72.54 BCM which represents about 99.5% of the outflow volume released at GERD due to the main dam failure. The remaining water volume (about 0.36 BCM) is stored inside depressions distributed along the floodplains. The arrival of the first water drop to Roseires reservoir entrance was found to be after 6 h from the beginning of the GERD main dam failure. The first reach inundation map (spatial distribution of

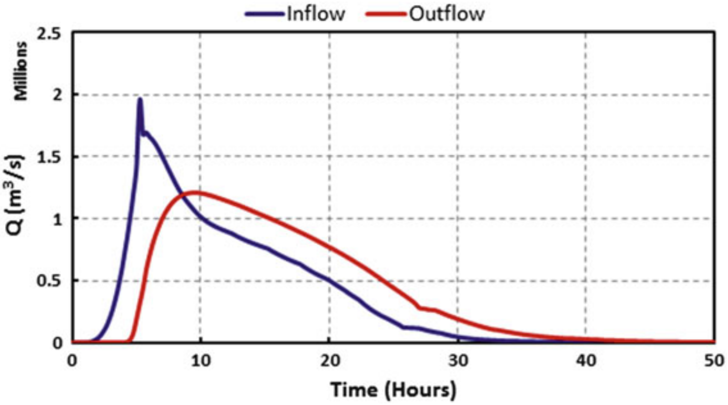

Fig. 5 Inflow and outflow hydrograph of the first reach

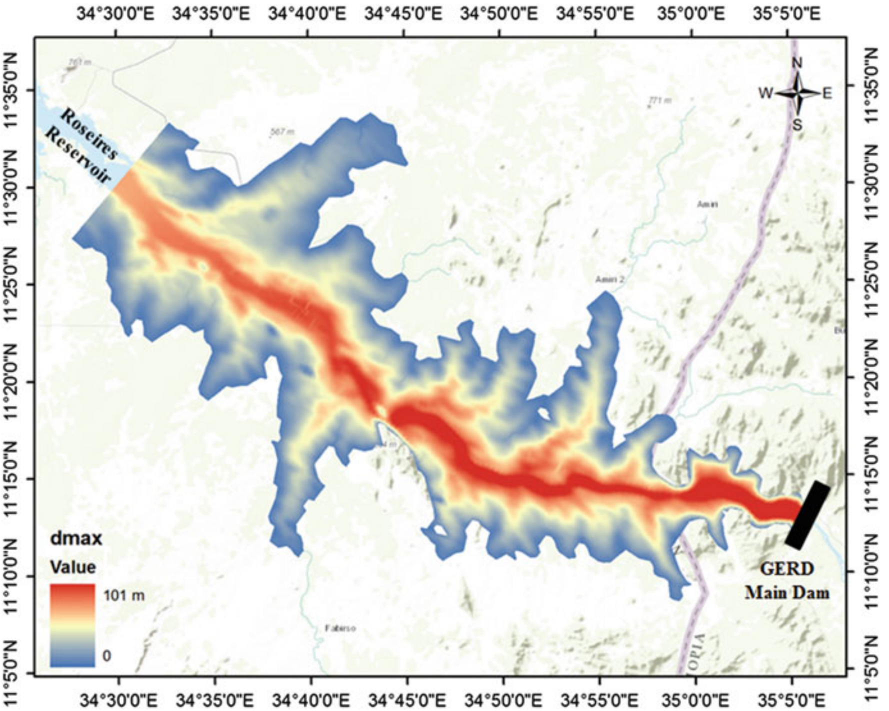

Fig. 6 Spatial distribution of maximum water depth along reach 1

maximum water depth) is presented in Fig. 6, while the spatial distribution of velocity along the first reach is presented in Fig. 7.

As depicted in Fig. 6, water depth at the upstream section of the first reach is 101 m where it is found to be about 55 m at the downstream section (entrance of

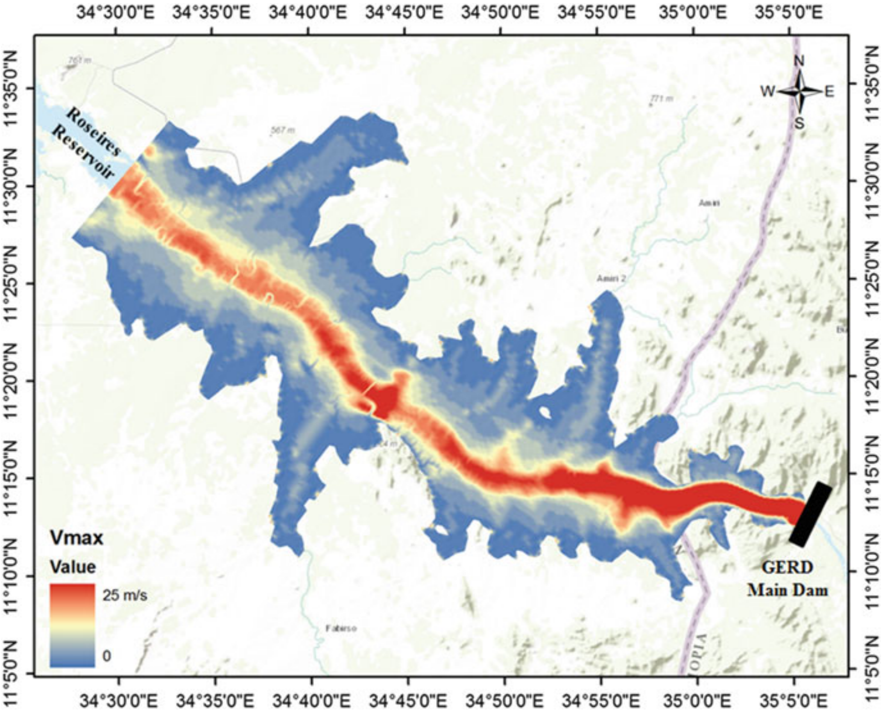

Fig. 7 Spatial distribution of maximum water velocity along reach 1

Roseires Dam reservoir). The flood water due to GERD main dam failure covers about 1,130 km^2 including river and floodplains with a maximum spreading width about 30 km perpendicular to the river. The area covered by flood water presents about 26% of the selected grid area which proves that flood water is well contained inside the simulated area and matched with ground levels. Also, the maximum spread of water (30 km) is less than total grid width (60 km) which supports the same conclusion that flood water is well contained inside the simulated area. The maximum velocity along the first reach is 25 m/s as presented in Fig. 7. Also, Fig. 7 shows that the velocity at the entrance of Roseires Dam reservoir is 10 m/s. In addition to that, this figure shows higher velocities along river deep channel, and it decreases toward floodplains.

Similarly, the other five reaches are simulated. A summary of the simulation results of all reaches is presented in Table 2 given that the results of the fourth and fifth reaches are joined for simplicity.

As shown in the above table, water above Roseires, Sennar, and Merowe dams are 35, 24, and 6 m, respectively. The high depth at Roseires Dam will wash out the dam and add the stored water inside its reservoir to the released volume due to GERD failure. The same situation will occur at the two other dams (Sennar and Merowe dams) as the water depth above Sennar crest will reach about 24 m while it

Table 2 Summary of the hydraulic properties along the simulated reaches

Item	GERD-Roseires	Roseires-Sennar	Sennar-Al Khartoum	Al Khartoum – Merowe	Merowe-AHD
d_{max} U/S (m)	101	45	22	21	32
d_{max} D/S (m)	55	30	21	10	12
V_{max} U/S (m/s)	25	10.0	8.0	2.4	14.0
V_{max} D/S (m/s)	10	4.1	2.4	4.0	4.8
Water extend (km)	30	126.0	176	40	27
Q_p U/S (m^3/s)	1,959,730	1,315,100	608,880	94,144	329,080
Time to peak U/S (h)	5.00	11.50	41.00	134.0	312.75
Q_p D/S (m^3/s)	1,310,000	611,254	94,144	41,602	36,990
Time to peak D/S (h)	11.0	40.00	134.0	347.50	549.25
Early arrival time D/S (h)	6.0	26.5	100.75	280.5	486.75
H_{max} at US dam (m)	–	35	24	–	6

will be about 6 m above Merowe Dam crest level. Based on that, Roseires, Sennar, and Merowe dams will also fail due to GERD failure.

Furthermore, it is very clear that peak flows are decreasing toward the downstream except at Merowe Dam where it is increasing due to Merowe Dam failure and the release of its huge storage, and then it decreases again until reaching the entrance of Lake Nasser.

The peak inflow at Lake Nasser is found to be 36,990 m^3/s which represent about 2% of the peak outflow at GERD due to its failure.

Additionally, the spatial distribution maps of maximum water depths were developed for all reaches to evaluate the inundated areas. An example of the developed maps is presented in Fig. 8 which represents the third reach.

As shown in Fig. 8, the flood water due to Sennar dam failure covers about 29,873 km^2 including river and floodplains with a maximum spreading about 176 km perpendicular to the river. The area covered by flood water represents about 44.7% of the selected grid area which proves that flood water is well contained inside the simulated area and matched with ground levels. Also, the maximum spread of water (176 km) is less than total grid width (250 km) which supports the same conclusion that flood water is well contained inside the simulated area. On the other hand, Fig. 8 shows that the flood water due to Sennar dam failure which is located on the Blue Nile flows laterally toward White Nile and generates a negative surge wave along White Nile which will affect Jabal al-Awliya Dam (located on the White Nile just upstream of Al Khartoum City) which may be failed too.

Making use of the developed maps, the inundated areas and properties were evaluated and found to be about 25,400 km^2 of agriculture lands, roads, and buildings. The detailed inundated areas of each reach are presented in Table 3.

As shown in Table 3, there is no properties inundated along reach 1 which is due to this reach is located at the borderline between Ethiopia and Sudan and almost has no activities. Additionally, reach 3 has the largest inundated properties due to its flat nature as it is near Al Khartoum City.

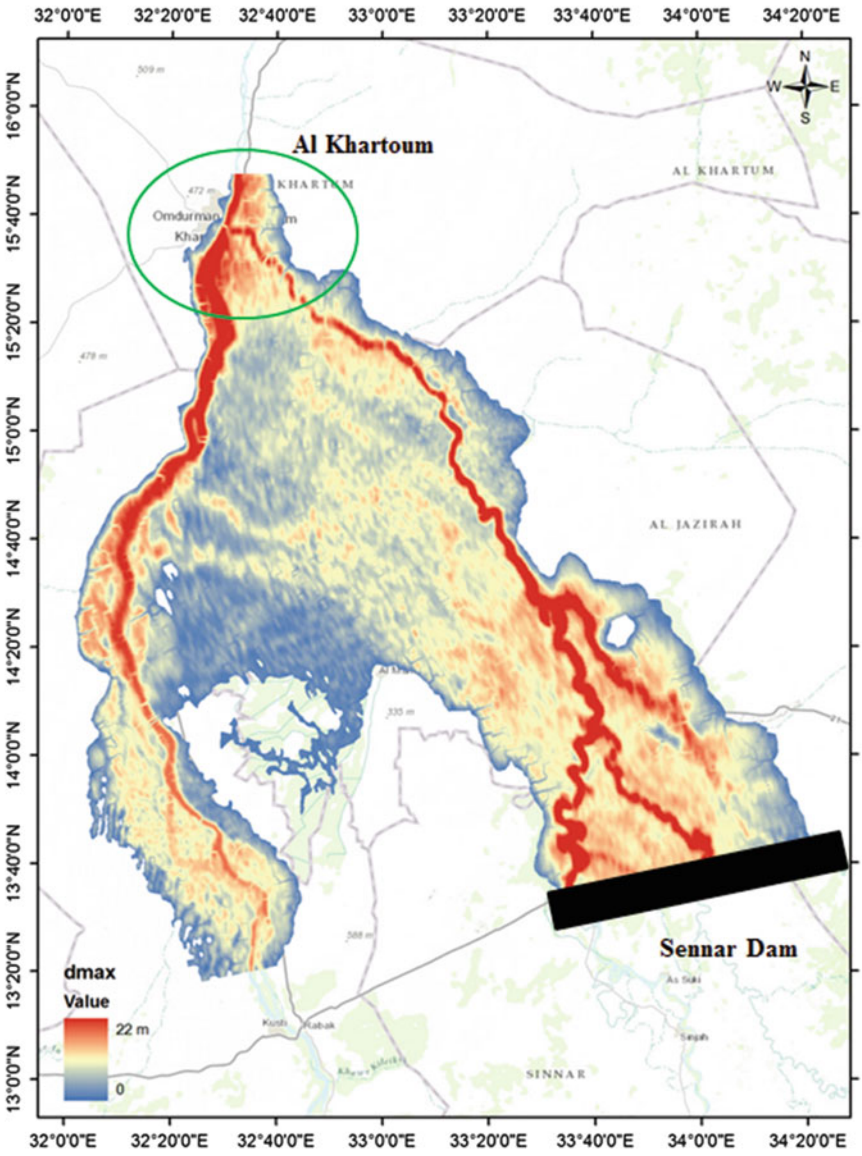

Fig. 8 Spatial distribution of maximum water depths along the third reach

Table 3 Inundated areas of each reach

Reach	1	2	3	4 and 5	6	Total
Area (km^2)	0	3,600	15,800	3,500	2,500	25,400

6 Impacts of GERD Failure on AHD

The Aswan High Dam (AHD) is the major control structure on the Nile River in Egypt. AHD protects Egypt from flood risks in addition to providing water during drought periods. AHD may be at risk in case of Ethiopian Dam (GERD) failure. As discussed previously, there are several scenarios for GERD failure. In each scenario, large amounts of water are predicted to enter Lake Nasser. The main goal of this chapter is to assess the risk to AHD due to GERD failure.

AHD has three outflow and spillage structures. Two of these structures (outflow tunnels and emergency spillway) deliver their flows to the Nile River downstream of the dam. The third structure is Toshka spillway. The assessment of the associated risk to AHD and the downstream structures along Nile River up to Alexandria was achieved based on the methodology presented in Fig. 9.

As shown in Fig. 9, the applied methodology begins by the insertion of inflow hydrograph into Lake Nasser which has a certain initial storage. The outflow tunnels and Toshka spillway are assumed to work at the same time from the beginning of the simulation according to water level. The outflow tunnels are assumed to release the normal outflow which can be accommodated safely by the downstream river cross sections in addition to crossing and control structures (the normal outflow from tunnels is 250 million cubic meters per day [17]). If the water level upstream of AHD is lower than or equal to the maximum allowable water level (+182.0 m), the dam body and the downstream structures and floodplains will be safe. Otherwise, the outflow from tunnels will be increased regularly up to the maximum capacity of the tunnels (11,000 m^3/s). If the increase of flow released from tunnels satisfies a safe water level upstream AHD, the dam body would be

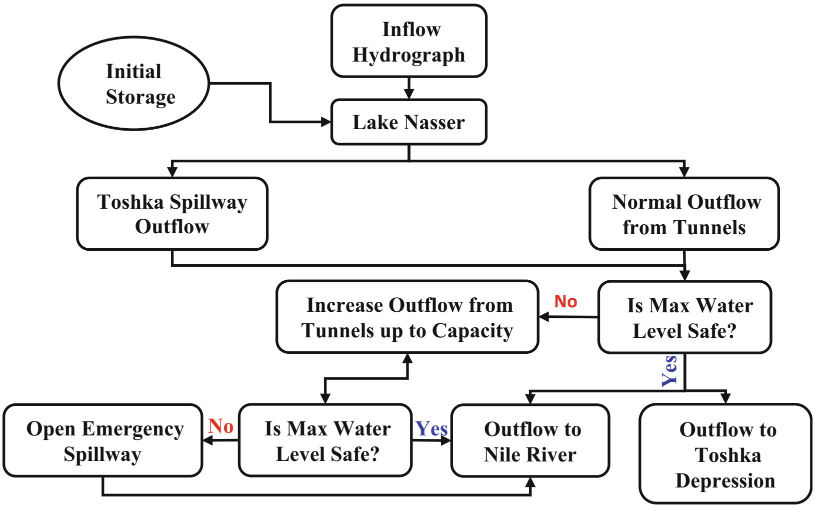

Fig. 9 Methodology applied to assess risk associated with AHD

safe, while the downstream structures and floodplains will be at risk. If the upstream water level is greater than the maximum allowable water level, the emergency spillway will be fully open to provide additional safety to the dam body, but the downstream structures and floodplains will be at high risk. At all cases, the peak outflow released to Nile River or Toshka depression is evaluated.

A mass balance algorithm was developed as a part of this study using the MATLAB software to apply the abovementioned methodology. The mass balance equation applied is as presented in Eq. (1):

$$Q_{\mathrm{in}} - Q_{out} = \frac{\Delta S}{\Delta t} \tag{1}$$

where Q_{in} is the inflow rate (m^3/s), Q_{out} outflow rate (m^3/s), ΔS change of storage (m^3), and Δt simulation time interval (s).

The developed algorithm simulates the target scenario as follows:

- First, the simulated period is divided into several intervals using constant time step.
- At the beginning of the time step, the inflow rate and the corresponding reservoir water level are known.
- Knowing the reservoir level, the outflow rates are calculated.
- Accordingly, the stored volume and the corresponding water level inside the reservoir at the end of the time step are calculated.
- The previous three steps are repeated at each time step up to the end of the simulated period.

Four initial water levels in Lake Nasser are simulated. The first water level is equal to 147 m which correspond to zero live storage (empty reservoir). The second water level is equal to 166 m which correspond to 50 BCM live storage (half full reservoir). The third water level is 175 m which are used in the AHD operation rule as the maximum storage level before flood seasons to allow for a reasonable storage volume before spillage (flood control). The last water level is equal to 178 m which are equal to spillway crest level (full reservoir). The live storage corresponding to each initial reservoir water level is presented in Table 4.

At each water level, there are four inflow hydrographs considered during this study. The first inflow hydrograph is equal to the flow hydrograph due to the failure of GERD and other dams only without additional regular flow. Regarding the second to fourth cases, failure hydrographs were assumed to occur during low, average, and high flood seasons, respectively.

Sixteen scenarios are considered in this study as presented in Fig. 10. As can be concluded from Fig. 10, scenarios 1–4 are assigned for the empty reservoir, scenarios 5–8 are assigned for the half-full reservoir, scenarios 9–12 are devoted

Table 4 Lake Nasser live storage corresponding to initial water level

Water level (m)	147	166	175	178
Live storage (BCM)	0	50.0	89.7	105.9

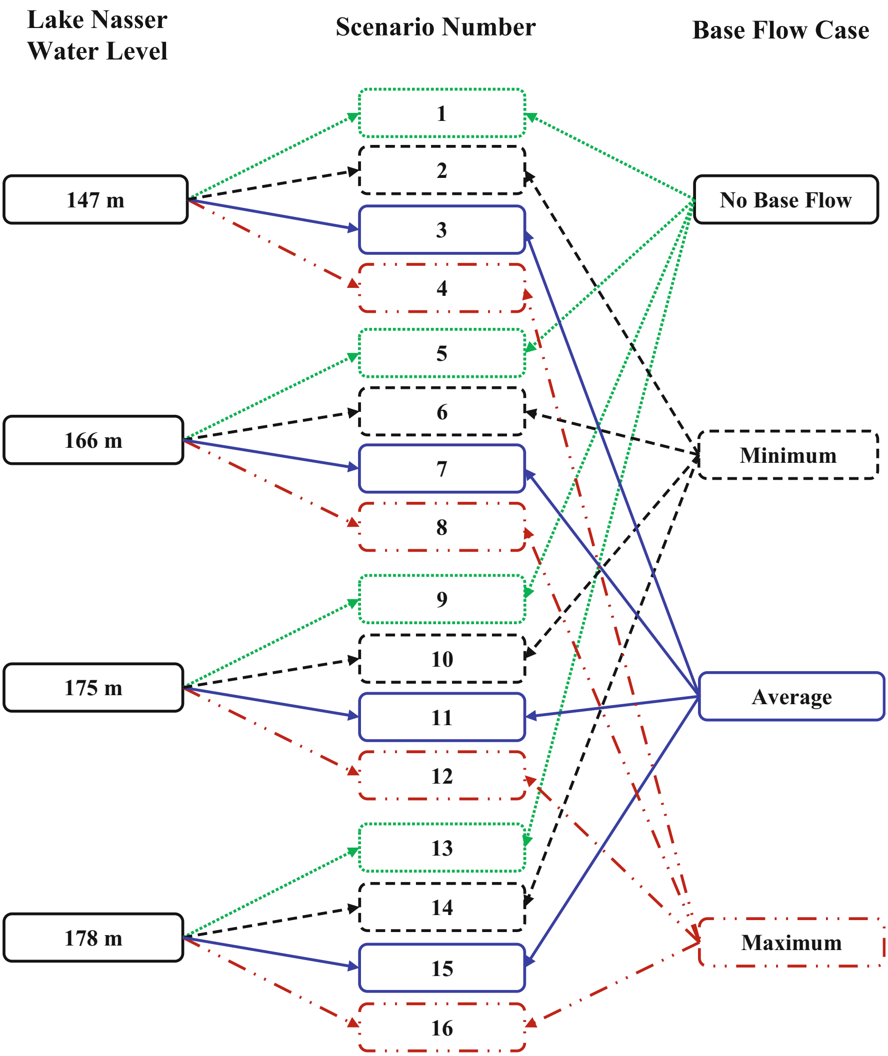

Fig. 10 AHD assessment scenarios

to maximum storage before flood seasons, and scenarios 13–16 are devoted to spillway crest level.

As presented earlier, the inflow hydrograph to Lake Nasser has a peak value equal to 36,990 m^3/s and the total volume of 57.3 BCM. The total volume of the failure hydrographs will totally arrive at Lake Nasser within about two and half months from the beginning of GERD failure. Because the transmission losses are not considered during the hydraulic simulation, it will be taken into consideration during the assessment of AHD due to GERD failure. The transmission losses are assumed to be equal to 10% of the inflow hydrograph.

Although the GERD failure hydrograph has a base time of two and half months, the simulation will be carried out for 1 year to allow for a reasonable assessment of AHD. All scenarios will be started in August and ended in July.

As discussed above, there are four base inflow cases according to flood season at which GERD failed. In the first case, which is a hypothetical case, the inflow hydrograph to Lake Nasser is assumed to totally enter to Lake Nasser with no base flow due to traditional floods. The inflow hydrographs (considering the transmission losses) of GERD failure with no base flow due to traditional floods are presented in Fig. 11.

The base inflows due to traditional floods are calculated for the other three inflow cases (minimum, average, and maximum base inflow). The base inflow is assumed to be equally distributed during each month of the simulation period. The annual base inflow volume is found to be 145.0 BCM in case of maximum flood, 84.0 BCM in case of average flood, and 40.9 BCM in case of a minimum flood. The base inflow hydrographs to Lake Nasser are presented in Figs. 12, 13, and 14.

As shown in Figs. 12, 13, and 14, the maximum inflow rate is 3,460 m^3/s for minimum base inflow case, 8,590 m^3/s in case of average base inflow, and 12,740 m^3/s for maximum base inflow case. Also, the minimum inflow rate is 620 m^3/s for minimum base inflow case, 560 m^3/s in case of average base inflow, and 1,250 m^3/s for maximum base inflow case.

The simulations of the 16 scenarios under consideration are carried out, and their results are presented in Tables 5, 6, 7, and 8.

As can be concluded from Table 5, there is no upstream harm associated with AHD in scenarios 1–11 in addition to scenarios 13 and 14 as the maximum water level does not exceed the maximum allowable water level (+182.0), whereas AHD is at risk from the upstream side due to the other three scenarios (12, 15, and 16) as the maximum allowable water level is exceeded.

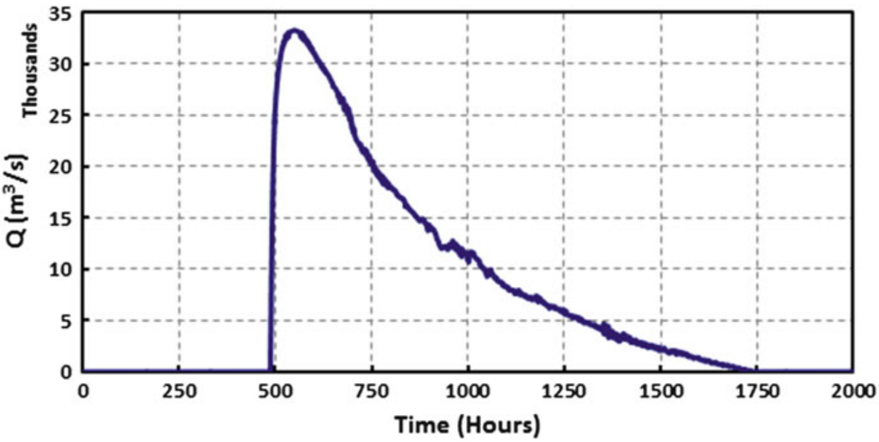

Fig. 11 Inflow hydrograph to Lake Nasser in case of no base flow

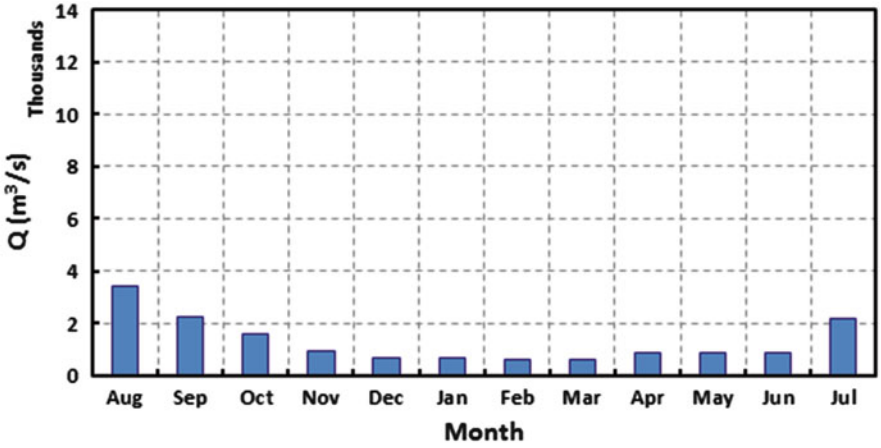

Fig. 12 Inflow hydrographs to Lake Nasser in case of minimum base flow

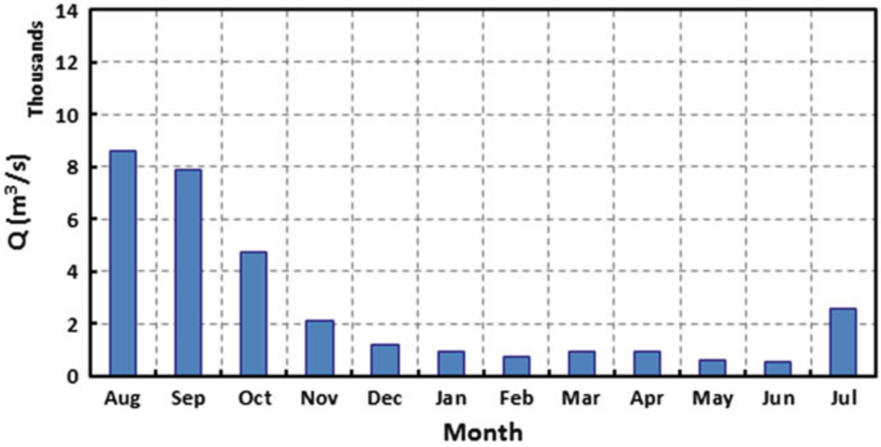

Fig. 13 Inflow hydrographs to Lake Nasser in case of average base flow

Table 6 depicts that there is a risk to the AHD structures (body) from the downstream side in addition to the risk associated with the downstream floodplains and structures in scenarios 10–16 in addition to the eighth scenario. The other scenarios do not constitute any harm or risk to AHD body or the downstream floodplains and structures as the maximum daily outflow released to the downstream does not exceed the safe release.

Table 7 shows that Toshka spillway will divert up to 2,290 m^3/s (198 million cubic meters per day) to Toshka depression of the inflow volume to Lake Nasser. Also, Table 7 shows that there is no outflow through Toshka spillway in scenarios one to three in addition to scenarios five and six.

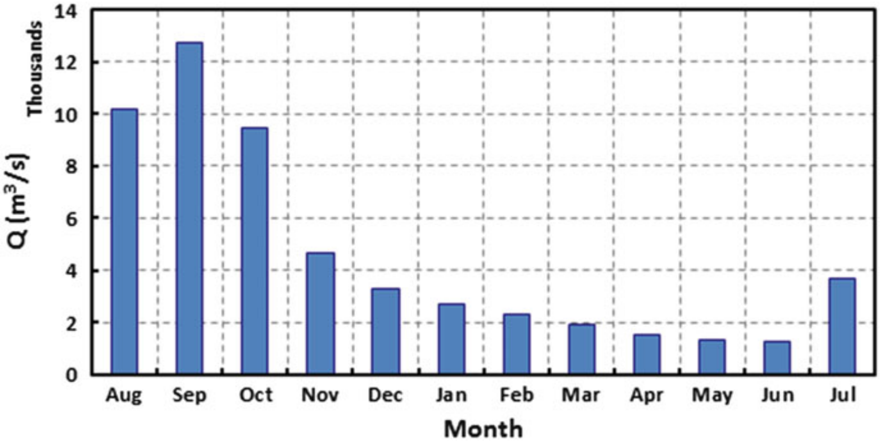

Fig. 14 Inflow hydrographs to Lake Nasser in case of maximum base flow

Table 5 Maximum water level in case of main dam failure

	Initial water level (m)			
	147	166	175	178
Base flow	Maximum water level (m)			
No	163.5	174.1	180.9	182.0
Minimum	167.0	176.7	182.0	182.0
Average	173.6	181.2	182.0	**182.5**
Maximum	179.1	182.0	**182.5**	**183.4**

Table 6 Maximum tunnel flow in case of main dam failure

	Initial water level (m)			
	147	166	175	178
Base flow	Maximum outflow through tunnels (m^3/s)			
No	2,894	2,894	2,894	**4,414**
Minimum	2,894	2,894	**3,765**	**7,074**
Average	2,894	2,894	**8,611**	**11,000**
Maximum	2,894	**5,462**	**11,000**	**11,000**

Table 8 shows that there is an additional harm to AHD from the downstream side in addition to the downstream floodplains and structures due to emergency spillway flow. The emergency spillway will release additional water to the downstream in scenarios 12, 15, and 16. The maximum daily outflow released through emergency spillway is found to be about 470 MCM.

Table 7 Maximum Toshka spillway flow in case of main dam failure

	Initial water level (m)			
	147	166	175	178
Base flow	Maximum outflow through Toshka spillway (m³/s)			
No	0	0	990	1,583
Minimum	0	0	1,583	1,583
Average	0	1,158	1,583	1,867
Maximum	58	1,583	1,865	2,290

Table 8 Maximum emergency spillway flow in case of main dam failure

	Initial water level (m)			
	147	166	175	178
Base flow	Maximum outflow through emergency spillway (m³/s)			
No	0	0	0	0
Minimum	0	0	0	0
Average	0	0	0	**4,426**
Maximum	0	0	**4,423**	**5,482**

Several assessment scenarios and cases are investigated in this section to assess the impacts of GERD main or saddle dam failure on AHD and its downstream floodplains and structures. The assessment reveals the following outcomes:

- There is no significant difference between GERD main or saddle dam failure regarding the impacts on AHD.
- There are no negative impacts on AHD and its downstream floodplains and structures due to GERD failure in case of empty AHD reservoir as the maximum water level will not exceed the maximum allowable level and the maximum release to the downstream will not exceed the safe limit.
- There is a severe impact on AHD and its downstream floodplains and structures in case of the full reservoir as the water level exceeds the maximum allowable water level in some scenarios, and the released flow to the downstream exceeds the safe limit in all scenarios.
- In case of the half-full reservoir, the downstream floodplains and structures will be at risk at scenario number eight (maximum base flow) as the outflow through tunnels exceeds the safe flow.
- In case of maximum water level at the beginning of the water year (175.0 m), the downstream will be at risk in scenarios 10–12 (minimum, average, and maximum base flow, respectively), while the dam body will be at risk in scenario number 12 (maximum base flow) only. On the other hand, the dam body and its downstream will be safe in case of the ninth scenario.

- The emergency spillway has to work in scenarios 12, 15, and 16 which increases the risk to the downstream floodplains and structures.
- Toshka spillway with its existing conditions and dimensions diverts up to 198 MCM per day.
- Toshka depressions collect about 11.5 BCM during the simulation of the worst-case scenario (scenario 16) which extended for 1 year.
- Toshka spillway capacity has to be increased to provide additional protection to AHD and its downstream floodplains and structures.
- Several widths are investigated for Toshka spillway. The minimum spillway width at which AHD body and its downstream will be fully protected is found to be 3,000 m.

7 Conclusions

The literature review and the collected data show that GERD has high failure probability due to the geological nature of its location.

GERD failure simulation shows that the peak outflow at GERD approached two million cubic meters per second and occurred within 5 h from the beginning of GERD failure. Also, the peak inflow at the entrance of Lake Nasser approached 37 thousand cubic meters per second and occurred within about 3 weeks from the beginning of GERD failure. The inflow to Lake Nasser is about three times of the maximum inflow at wet seasons (the maximum measured peak inflow at wet season was about 13,000 m^3/s), so it may be harmful to Aswan High Dam body.

Also, the simulation shows that Roseires, Sennar, and Merowe dams will be washed out due to GERD failure. Moreover, Al Khartoum City will be flooded by a water depth of about 10–15 m above natural ground level. The flood water due to GERD failure will arrive at Al Khartoum City within 4 days from the beginning of GERD failure and will reach its maximum depth within 2 days at most. So, Al Khartoum City will be in a severe condition very short after GERD failure and will be converted into a large lake during 6 days only from the beginning of GERD failure. Accordingly, it is very clear that Sudan will be affected significantly in case of GERD failure.

Regarding the impacts on AHD, it depends on the water level in Lake Nasser at the time of GERD failure. In case Lake Nasser is full or near full, the dam body will be at risk and may suffer severe damage. Also, the downstream properties will be at risk, especially, Aswan reservoir and all crossing structures along Nile River from Aswan to Alexandria in addition to devastating risks to land and human lives due to a high release from Lake Nasser which may exceed the cross sections capacity.

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Environmental Impacts of the GERD Project on Egypt's Aswan High Dam Lake and Mitigation and Adaptation Options

El-Sayed Ewis Omran and Abdelazim Negm

Contents

Abstract Egypt, which suffers from water scarcity, has been listed among the ten top countries that are threatened due to the rapidly increasing population. With growing concerns about climate change and possible impacts on water shortage, human intrusion and development processes have had undeniable adverse impacts

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on maintaining healthy lakes. Aswan High Dam (AHD) Lake is considered a source of water to minimize the water scarcity problem. Lake Nasser is facing many challenges. One of these challenges is the Grand Ethiopian Renaissance Dam (GERD). GERD is now under construction on the Blue Nile River in Ethiopia. The question still to answer is “will the GERD affect Lake Nasser?” This chapter focuses on two objectives: first is to evaluate the land resources of Lake Nasser and second is to study the impact of GERD on AHD Lake. The challenges facing the sustainable development of AHD lake and their solutions are identified and discussed.

First, soils surrounding Lake Nasser, i.e., Kalabsha, Toshka, El- Dakka, Abu Simbel at the western side of the lake, and Allaqui area on the eastern side, were deposited due to water action (wind action was not evaluated in this study). Wadi soils are heterogeneous and stratified and composed of subrounded grains; this may be linked to the distance of transportation. The parent materials of these soils are wadi sediments, shales, and Nubian sandstones. Sedimentation in Lake Nasser is estimated to be around 31 billion cubic meters, which is enough to be absorbed over 300–400 years. The silt is not regularly distributed on the lake floor but is mostly accumulating (more than 30 m in 1992) at the site of the second waterfall around the ancient city of Wadi Halfa. The amount of silt deposited is estimated as 109 million cubic meters per year. The sedimentation of silt can lead to the blockage of a large part of Nasser’s Lake around the second waterfall at Wadi Halfa. This may result in a significant loss of water due to evaporation and leakage. Because the Lake Nasser reservoir is approaching its maximum storage capacity, the depressions west of Lake Nasser in the southwestern desert of Egypt (Toshka Lakes) are a natural flood diversion basin to reduce possible downstream damage to the Nile Valley caused by exceptional flooding.

Second, the impacts of GERD on AHD are a reduction in the water share to Egypt, reduction in power generated at AHD, increased salinity of Egypt’s agricultural lands, increase in seawater intrusion, and infilling Lake Nasser/Lake Nubia with sediment. Since this chapter aims to suggest some measures to help the decision/policy makers to solve the water shortage problem caused by GERD, a number of management actions and strategies are suggested to secure Egypt’s water demands and to minimize the water scarcity problems. Third, the actions identified to minimize the water scarcity in Egypt are reducing evaporation losses from Lake Nasser, maximizing the use of groundwater wells and rainwater in Egypt, seawater desalination, sewage treatment and reusing irrigation water, maximizing water use efficiency, and starting giant projects out of the narrow valley and delta.

The yearly average of the daily evaporation rate from Lake Nasser is 6.3 mm day^{-1}. The average volume of the annual water loss by evaporation is about 12.5 milliards cubic meter. To save more than 1 million cubic meters of water loss from Lake Nasser due to evaporation, 0.500 km^2 must be covered with circular foam sheets with an efficiency of coverage equal to 90%. The circular foam system can be adjusted such that it has no impact on the passage of sunlight to aquatic life. The expected total amount of saved water using all the above strategies equals 40 BCM, which exceeds the expected losses caused by GERD. Adopting all or a combination of the suggested management actions and strategies could help reduce the impact of GERD on Egypt.

Keywords Egypt, GERD, Lake Nasser, Water scarcity, Land resources, AHD

1 Introduction

Egypt has been listed among the top ten countries suffering from water shortages by the year 2025, partly due to the rapidly increasing population [1]. More than 96% of Egypt' all freshwater resources are supplied by the Nile River. Growing concerns about climate change, human intrusion, and development processes could have adverse effects on maintaining a healthy environment in Egypt's lakes [2].

Water conflicts can arise in water-stressed areas among local communities and between countries because sharing a very limited and essential resource is extremely difficult. In 2011, the Ethiopian Government announced a plan to construct a hydroelectric dam on the Blue Nile River, 45 km east of its border with Sudan in Ethiopia, which has been named the Grand Ethiopian Renaissance Dam (GERD). It will create a lake with a volume of 74 BCM [3]. A major concern is how filling the huge reservoir will affect water security in Egypt, which relies almost totally on the Nile for its water supply. Depending on how long it takes (3–7 years) to fill the reservoir, the Nile flow into Egypt could be cut by 12–25% during the filling period [4]. A major shortcoming is the lack of gauges on the Blue Nile in Ethiopia, which means that data on the flow of the Blue Nile is inadequate [5]. The question still to answer is "will the GERD affect Lake Nasser?"

It is believed that the construction of GERD will affect Egypt's water quota through decreased discharge from the Aswan High Dam (AHD) [3]. The main adverse impact in Egypt will be a reduction in power generated at the AHD due to a fall in water levels of Lake Nasser. Furthermore, the AHD will reach the minimum operational level during 4 consecutive years in the case the first filling of the GERD occurs during dry years, which would significantly affect the water supply to Egypt.

To be able to properly address these problems, detailed information about water and land resources of AHD is important. Otherwise, this situation will never be properly addressed. Despite the presence of the few studies that have been conducted to investigate Lake Nasser, this chapter's aim is to evaluate the challenges facing the sustainable development of AHD Lake and to study the GERD influence on AHD. Recommendations to minimize the GERD impact on AHD and water scarcity in Egypt were presented.

2 Southern Egypt's Lakes

2.1 Toshka Lake

Toshka Lakes (Fig. 1) is the name given to recently formed endorheic lakes in southwestern part of Egypt, New Valley Governorate (El-Wadi El-Gadid). The Toshka area is the first site to host the population in the desert, by prehistoric man,

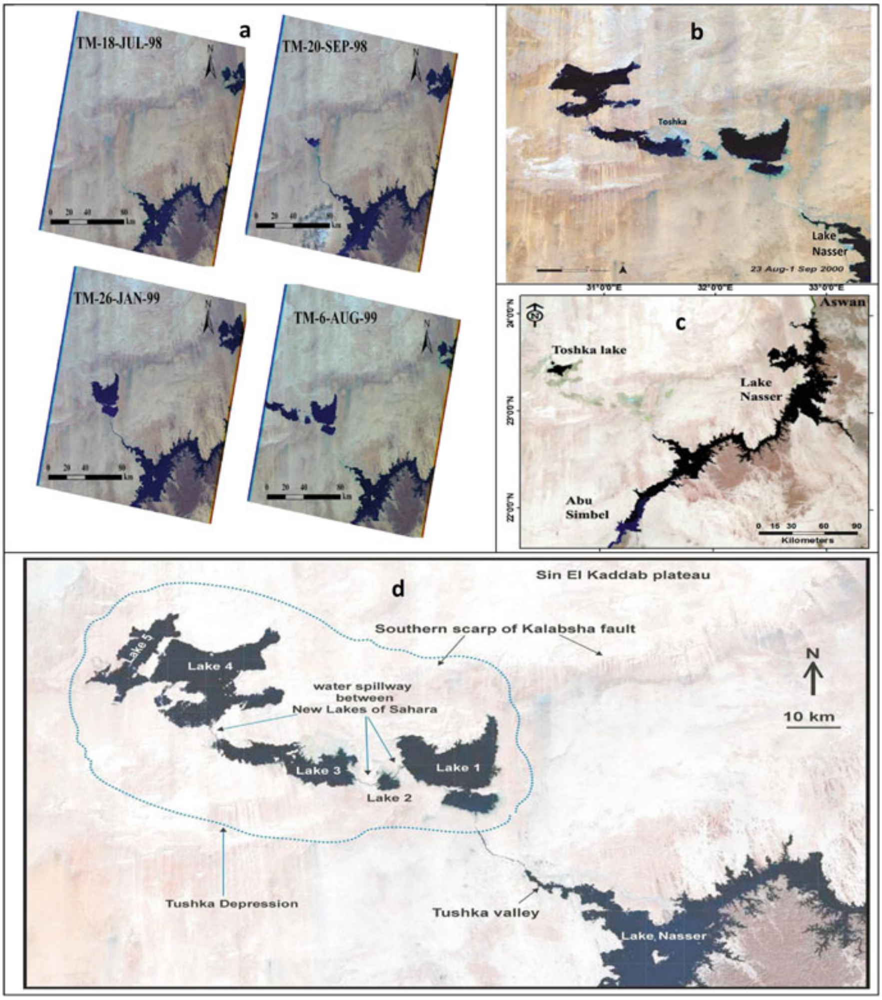

Fig. 1 A sequence of TM images of the Toshka Lakes [6] in 1998 and 1999 (**a**) and Landsat 8 taken in 2000 (**b**) and 2014 (**c**). Toshka Lakes were created by the diversion of water from Lake Nasser through a man-made canal into the desert (**d**)

and is a region of archaeological value, including the effects of and information about the origin of human civilization. Many dry valleys are connected to the surface of Lower Nubia, which discharged into the lake, and the valleys are Toshka and Wadi Aldka, where the headwaters are located in the plains of Nubia. The region is surrounded by hills in some parts of the Nubian sandstone, where there is a hilly landscape mainly in the form of hierarchical shape or continuous sandstone ridges. The Toshka Project was part of ex-President Mubarak's 1997 New Valley Project, comprising of building a system of canals to bring water from Lake Nasser through

Wadi Toshka for irrigation in the Western Desert. Toshka Lakes were made in the 1980s and 1990s to convey water from Lake Nasser to the Sahara Desert through a synthetic canal. Between 1998 and 2002, a series of unusually high-volume floods of the Nile increased the water level of Lake Nasser/Lake Nubia to beyond the capacity of the AHD. This problem prompted construction of a draw-down channel linking Lake Nasser with the Toshka Depression adjacent to Lake Nasser. The New Valley Project, which started in 2008 and ended in 2013, failed to reach its objectives due to poor soils, sand dune encroachment, and excessive evaporative losses.

Flooding of the Toshka Depression made four fundamental lakes with a most extreme surface area of around 1,450 km^2 – around 25.26 billion cubic meters of water. By 2006, the amount of stored water was reduced by 50%. In June 2012, water filled just the lowest parts of the main western and eastern basins – representing a surface area of 307 km^2 or approximately 80% smaller than in 2002. Water is totally absent from the central basin. Here in a "new valley," agriculture and industrial communities could be developed in the hope of supporting a home for millions of Egyptians. In the process of this development, four major lakes (Fig. 1) developed from the diversion of water from Lake Nasser via the canals. The Toshka Project was supposed to be completed by 2020. Obviously, things have not gone as planned in Egypt in the last few years, and ambitious, expensive undertakings like this have likely come to a standstill. The NASA photos (Fig. 1) also indicate that this project had come to a halt, with water in the associated Toshka Lakes evaporating in the hot desert extends.

2.2 *High Dam Lake*

Lake Nasser is one of the world's largest man-made (artificial) lakes in the world. It is located in southern Egypt and northern Sudan. Lake Nasser was created in the 1960s when the world famous High Dam was built. Together with the old Aswan Dam (built by the British between 1898 and 1902), it gives irrigation and electricity to all of Egypt. It was called for Gamal Abdel Nasser, president of Egypt from 1956 to 1970. The southern third of the lake is in Sudan and is called Lake Nubia. Lake Nasser lies between latitudes 23°58′, 20°27′ N and longitudes 30°07′, 33°15′ E (Fig. 2). The total length of the reservoir is about 500 km, with 150 km in Sudan (Lake Nubia) and 350 km within Egypt's borders [7, 8]. The lake has a surface area of 600 km^2 and an average width of 12 km (Fig. 2). The total storage capacity of the lake is 160×10^9 m^3, of which nearly 20% is considered dead storage (i.e., water is not released from this part of the lake regardless of the downstream needs). The lake covers an area of 5,248 km^2. It has a maximum depth of 130 m and mean depth of 25.2 m. Egypt's portion is 324 km long and has a shoreline of 7,844 km. Part of the area that Lake Nasser covers today was once the site of the temple of Abu Simbel, built by Ramses II around 1200 B.C. The temple was moved, but other sites of historical significance were submerged.

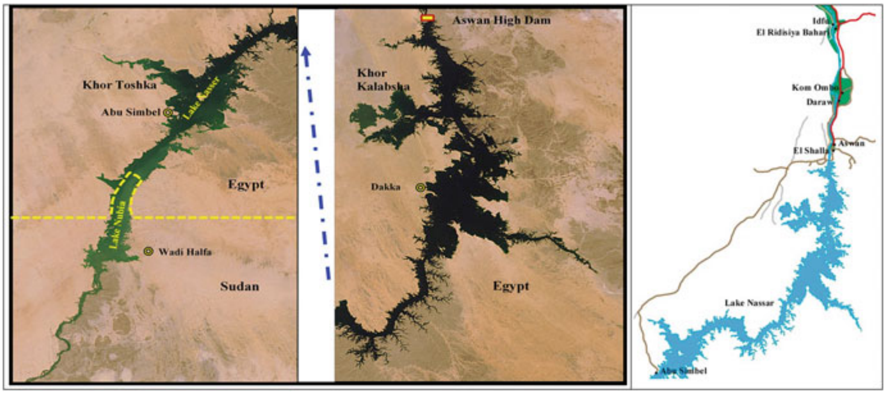

Fig. 2 Aswan High Dam Reservoir – Lake Nasser of Egypt and Lake Nubia of Sudan. Hydrogeologic map shows Lake Nasser, which is one of the world's largest artificial lakes

Because the Lake Nasser reservoir is approaching its maximum storage capacity, the depressions west of Lake Nasser in the southwestern desert of Egypt are used as a natural flood diversion basin to reduce possible downstream damage to the Nile Valley caused by exceptional flooding [7]. The major strategic units and the groundwater table level in Lake Nasser are shown in the hydrogeologic map (Fig. 2). Before the High Dam was built, 93% of the total annual suspended load of 124 million tons of sediment flowed directly into the Mediterranean Sea every year. AHD came in aid of this problem and retained 98% of the load within the reservoir, with only 2.5 million tons making it to the sea yearly.

Some studies have shown that sedimentation in the lake is expected to be around 31 billion cubic meters, which is enough to be absorbed over 300–400 years [9]. The silt is not regularly distributed on the lake floor but is mostly accumulated at the site of the second waterfall around the ancient city of Wadi Halfa. The rise of silt in the Wadi Halfa area in 1992 was higher than 30 m [10]. The thickness of the deposited silt gradually decreases to the north until it became less than a meter at Abu Simbel, and the silt is almost no longer north of that area. The amount of silt deposited between 1978 and 1995 was estimated at 1,418 million cubic meters or 109 million cubic meters per year [9]. The river's load varies from 1 year to another. The average load of the river at Wadi Halfa was 110 million tons (before the construction of the High Dam), reaching about 100 million tons (at Aswan) [11]. Sedimentation of the silt can lead to the blockage of a large part of Nasser's Lake around the second waterfall at Wadi Halfa. This may result in a significant decrease in water storage. However, the issue of silt deposition and its quantities and the most appropriate methods to obtain and benefit from it in agriculture has not been sufficiently studied.

Changes in water level interact with the physical features of Lake Nasser to yield both positive and negative geoenvironmental impacts [12–14]. A site of the new delta initiation (at the entrance of the lake), with maximum thickness, is concentrated in a zone lying between 350 km and 420 km of the dam. In Allaqui, the difference in water area between 1987 and 2000 was 91.9 km^2, and the difference in water extension was 25.54 km. In Allaqui, good soil (about 30,121 km^2) in the basin can be cultivated. The saturated water zone in Kurkur is close to the land surface and subject to transpiration and evapotranspiration. Kurkur vadose water can flow to the lake, and interflow water can migrate back to the land surface to evaporate. An area of 392 km^2 available for agriculture protects the Kurkur area from evaporation [12].

2.2.1 Soils Surrounding Lake Nasser

The soils surrounding Lake Nasser (Kalabsha, Toshka, El-Dakka, Abu Simbel) at the western side of the lake and Allaqui area on the eastern side were established as a result of water action [15]. Wadi soils are heterogeneous and stratified and are composed of subrounded grains; this may be linked to the distance of transportation. The origin of the clay minerals varies according to the lithological origin of soils. Kaolinite could be diagenetic formed in sandstone rocks and inherited in soils. Smectite may be derived from mica in the soils at the western side of the lake while from mica or volcanic ash at the eastern side. Chlorite of Wadi Allaqui soils was most probably derived from the primary minerals of the drainage basin of Wadi Allaqui. Illite was possibly formed because of changes on mica. Abu Al-lzz [16] reported that the Nile River terraces on both sides of the valley formed from sediments belonging to the Pliocene and Pleistocene. The Pliocene sediments in the southern part of the valley comprise of conglomerates, gravels, and sand. Those are distributed in some parts of the valley between Pleistocene and Holocene sediments of the flood plain and the two scarps bordering the valley. Pleistocene deposits constitute of sand and gravel originating in the Red Sea Mountains. Moreover, the formation of river terraces is related to three main factors, namely, changes in base level, changes in water volume and load, and changes in the hydrographic system of the Nile.

The parent materials of these soils are wadi sediments, shales, and Nubian sandstones [15]. On the western side of the lake, soils, each of Karkar, Kalabsha, Aldka, Sarah, Toshka, Abu Simbel, and Adindan, have consisted mainly of sandstone and shales. The soils of the Wadi Allaqui side east of the lake were established from igneous and metamorphic rocks. Karkar Valley is in the Nuba part west of Lake Nasser and runs until the Sinn El-Kedab Plateau (Fig. 3) bordering the valley from the west. The plateau extends to south Kharga with the area of 800 km^2 and a height of 180–550 m. The soils consist of different parent materials such as sandstone, limestone, clay, and sand transported by the wind. The sandy soil is prevailing in the region with a low content of salt. Kalabsha is located about 75 km south of the Aswan City. It extends from the Sinn El-Kedab Plateau (Fig. 3) in the direction of the northwest of Lake Nasser. Kalabsha Khor exists in the lower part of the Valley Kalabsha, starts from Lake Nasser, and extends towards the west for a distance of 10.5 km with an average width of about 3 km. It is divided into two branches: the northern branch continues its extension toward the northwest for a distance of 5.5 km with an average width of 1 km, and the southern branch continues its extension

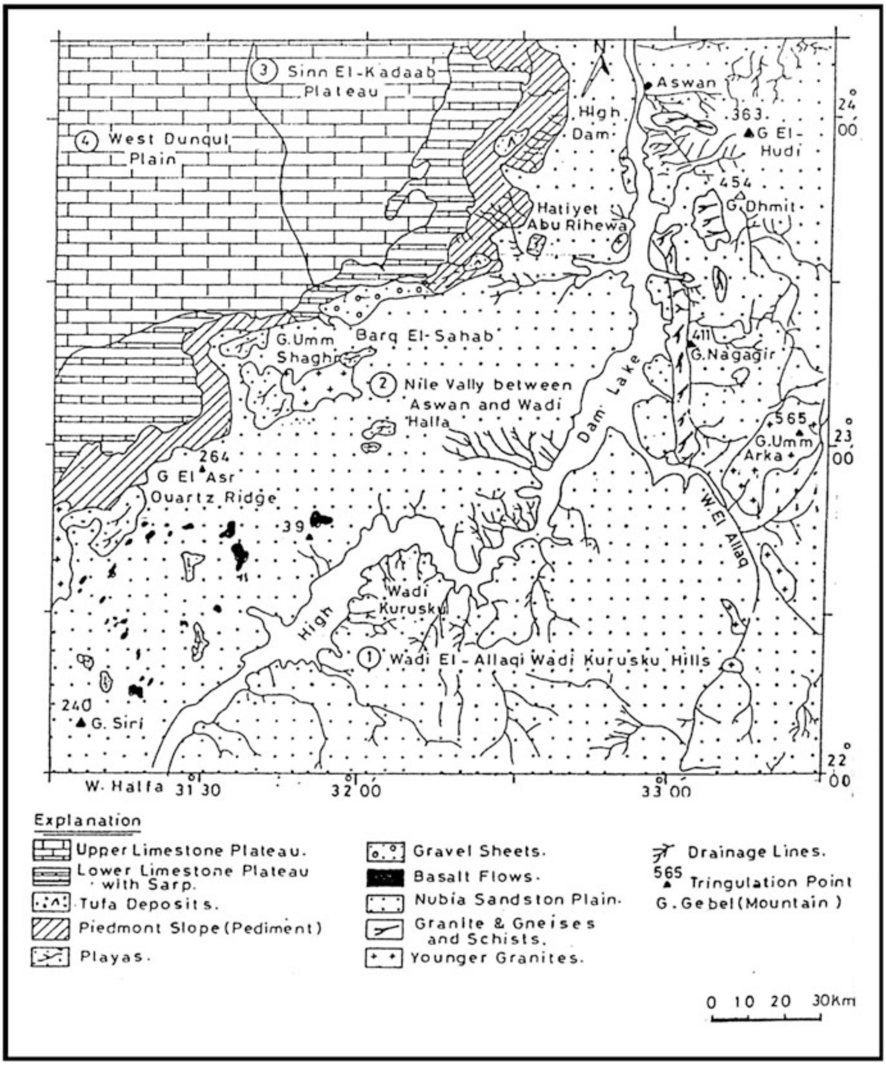

Fig. 3 Soils surrounding Lake Nasser

toward the southwest for a distance of 11.5 km with an average width of about 1.1 km.

Between Kalabsha and Aldka, there is a kaoline mine (kaolinite mineral), with thickness ranging from a few centimeters to over 5 m. A thin veneer of wadi deposits covers these deposits. Some single hills exist such as Marawah Mount (+270 m). Soft sediments are found in a low circular shape like Aburihwa Playa, located north of these Marawah Mount, with an area of about 30 km^2. The soil texture is often clay loam with a thickness of about 10 m.

Sarah Khor soils are located on the western bank of Lake Nasser and lie about 350 km south of Aswan, which is part of the plain of Lower Nubia. There are a few sand dunes and rocky bumps on the surface in some locations, and there are hills and plateaus separate (Mesas) of the Nubian. Many wadis exist in the area in which the most important and the longest are Sarah Khor.

Shallow sandy soils occupy part of the region, while the deep sandy soils occupy relatively small areas. Most of the soils (sandy or shallow sandy) are less than 50 cm in depth. The shallow sandy soil area is about 89,000 acres. The surface is covered with small-sized pebbles and it has low salinity that rarely exceeds 1.3 dSm^{-1}. The amount of $CaCO_3$ ranges from 1.1 to 4% and up to 15% or more on some sites [17]. The deep sandy soils occupy a small area (13,000 acres) and have a small gravel on the surface, very low salinity (less than 1 dSm^{-1}), and little $CaCO_3$. The dominant clay minerals [15] in Lake Nasser consist of kaolinite, montmorillonite, illite, and chlorite, but the kaolinite is dominant in the sandstone soils, a good kind of crystallization (well crystalline), while the transported sedimentary soils have weak crystallization of kaolinite.

The Adindan soils are located in the far south of Egypt, at the Egyptian-Sudanese border. Many valleys cut the region including Khor Adindan. The following soils are identified:

1. Deep sandy soil (11,448 acres) of which the soil surface is covered with a thin layer of sand, gravel, and mixed soils. Soil salinity ranges from 6 to 11 dSm^{-1} and $CaCO_3$ ranges from 2 to 14%.
2. Medium deep sandy soil (19,788 acres) ranges from 50 to 100 cm of which the soil surface is covered by desert pavement, mixed with gravel sand. Salinity is ranging from 7 to 10 dSm^{-1} and $CaCO_3$ ranges from 7 to 14%.
3. Shallow sandy soils (2,009 acres) at a depth of 25–50 cm, with some of fine-layered, rock Nubian sandstone at depths close to the surface. The salinity ranges from 3 to 11 dSm^{-1}, and $CaCO_3$ ranges from 2 to 14%, depending on the location.
4. Very shallow sandy loam soils (15,605 acres) at a depth of 25 cm. It is bounded on the bottom of the Nubian, mixed with gravel with sand through the layers of the soil at different rates depending on the location. The salinity ranges from 7 to 61 dSm^{-1} and $CaCO_3$ ranges from 3 to 7%.

3 Impact of GERD Project on AHD

A large-scale dam named the Grand Ethiopian Renaissance Dam (GERD) is under construction on the Blue Nile River in Ethiopia. A possible positive impact of GERD on Egypt is sediment load that will be retained. This will increase the lifetime of downstream infrastructures (i.e., AHD) and increase AHD reservoir active storage capacity. It is estimated that more than 50% of the sediment at Aswan is originated from the Blue Nile. However, dam's failure, including the GERD, can result from any one of these, or a combination, due to the following causes [3]: (1) prolonged periods of rainfall and flooding (the cause of most failures); (2) the presence of geological structures such as fault, joint zones, and folds in the rocks; (3) reservoir silting and sediment accumulation in the dam's reservoir due to insufficient dam spillways; (4) landslides into reservoirs, which cause surges that result in overtopping; and (5) earthquakes, which typically cause longitudinal cracks at the tops of embankments, leading to structural failure. The dangerous impacts of GERD on Egypt will be as follows:

3.1 Reduction in the Water Share of Egypt

One of the first impacts of GERD will be reducing Egypt's water share up to 5%, which likely will have a small effect on safe navigation [18]. Reduction in the water share of Egypt will result in securing the future supply of water for drinking, agriculture, and industry [19]. Water deficit in the river with an average annual income of 10 billion cubic meters will be the effect on Egypt. The High Dam contains about 140 million cubic meters, and the GERD fills about 70 million cubic meters. This is a very large quantity. If Ethiopia fills the dam within 7 years, this will not happen, and despite the length of time, the Egyptian people cannot bear the shortage of this water quantity. This means that Ethiopia will reserve during the 7 years 10 million cubic meters to fill the dam. Consequently, Egypt will have a dangerous stage, which did not pass through the ages as the lean years mentioned by the Koran.

3.2 Reduction in Power Generated at Aswan High Dam

When the water level of Lake Nasser is decreased, there will be a reduction in power generated at AHD. Reduction in the electricity production of the AHD reservoir will be between 20 and 30% [18] during the impound and operation of GERD especially during the drought period. Moreover, risks to Egyptian water supply and energy production depend on the initial storage in Lake Nasser when filling begins, the hydrologic conditions that occur during the filling period, the agreed annual release from the GERD, the operational policies of the AHD, and all upstream reservoirs [20]. The AHD is deemed to be operated primarily to meet downstream demands that total 55.5 BCM/year. The minimum elevation for power generation and downstream releases is 147 m (31.9 BCM). The elevation ranges from 175 to 182 m (121–167 BCM), which is reserved for emergency storage or flood protection operations. Pool elevations above 178 m are supposed to begin spilling into the Toshka canal [21]. A drought management policy reduces deliveries to downstream water users by 5% as the storage volume in Lake Nasser falls below 60 BCM (159.4 m), 10% below 55 BCM (157.6 m), and 15% below 50 BCM (155.7 m) [22].

If a larger portion of Egypt's share of the Nile is blocked, the alternative solution for Egypt would be to use the water in Lake Nasser, which is supposed to have water reserves for 10 years. Therefore, the problem is that the levels of Lake Nasser will decrease and cannot generate electricity. Since the construction of the High Dam in the 1970s, Egypt passed two considerable periods (8–10 years). There was a huge water surplus and two periods of low water. Egypt now lives seven lean (water decreases) years as mentioned in the Koran.

3.3 Increased Salinization of Egypt's Agricultural Lands

Increased waterlogging and subsequent soil salinization of Egypt's agricultural lands in the Nile Delta was affected by the increased upstream withdrawals, resulting from GERD operation [3]. The water table has risen along the Nile Valley since the construction of the AHD is confirmed by piezo measurements [23]. In low-lying areas, the water table is near the ground surface. Water downstream from the AHD has a higher salinity than water entering the reservoir due to high evaporation rate [24]. Nile water is reused several times before being discharged to the sea and each time is becoming saltier. As a consequence, the agriculture lands in Upper Egypt will decrease by 29.47% and in Delta will decrease by 23.03% [18]. The most critical factor in predicting, managing, and reducing salt-affected soils is the quality of irrigation water being used (the main sources of salinity in the Delta soils are irrigation water, Mediterranean saline water, and the high-level water table). Besides affecting crop yield and soil physical conditions, irrigation water quality can affect fertility needs, irrigation system performance and longevity, and how the water can be applied.

A high concentration of salt in the irrigation water has a deleterious impact on soil fertility and crop production and is a limiting factor for some non-salt-tolerant crops. Farmers use progressively more chemical fertilizer since perennial irrigation was instituted. Artificial fertilizers were used before the AHD. The nutrients of the soil washed down from the Ethiopian Highlands were relatively low in nitrogen and so that was supplemented for centuries. Therefore, the AHD has been responsible for Egypt depending more on artificial fertilizers, but not entirely. There are only three principal sources of hazardous salts in Nile Delta soils. These three types are irrigation water, shallow water table and logging, and seawater intrusion [25]. Figure 4 displays the distribution of soil salinity in the Nile Delta.

3.4 Increase in Seawater Intrusion

Increase in seawater intrusion in coastal aquifers in the North Delta has been threatening groundwater quality and increased salinity in these reservoirs. Mohamed and Elmahdy [26] show three scenarios (Fig. 5) of seawater intrusion along the

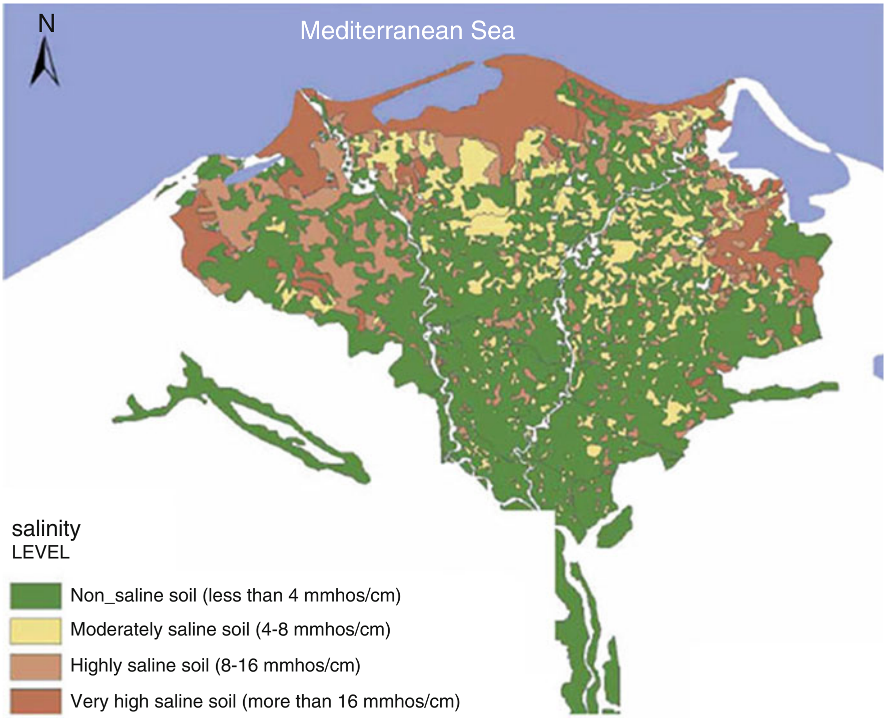

Fig. 4 Salinity distribution in the delta lands [25]

Egyptian Nile Delta as a result of GERD construction and groundwater table depletion, which is a common contamination problem in the coastal aquifer. The results show that the Nile Delta (which is part of the coastal aquifer) demonstrates the vulnerability that is likely to increase due to groundwater table depletion and seawater intrusion, as well as soil salinization. In turn, soil salinization will increase the probability of earth subsidence, geotechnical engineering problems, and agricultural degradation. The results obtained reveal that areas of about 2,677 and 4,675 km^2 will experience seawater intrusion when the groundwater table depletes, respectively, by 2 and 5 m below sea level (Fig. 5). These areas could be reduced if the number of the GERD spillways was increased.

3.5 *Environmental Degradation*

Environmental degradation and an increase in pollution are resulting in an imbalance of the natural system in North Lakes due to water shortages. Deserting agricultural lands, water pollution, fish farms, and disastrous consequences will be due to GERD.

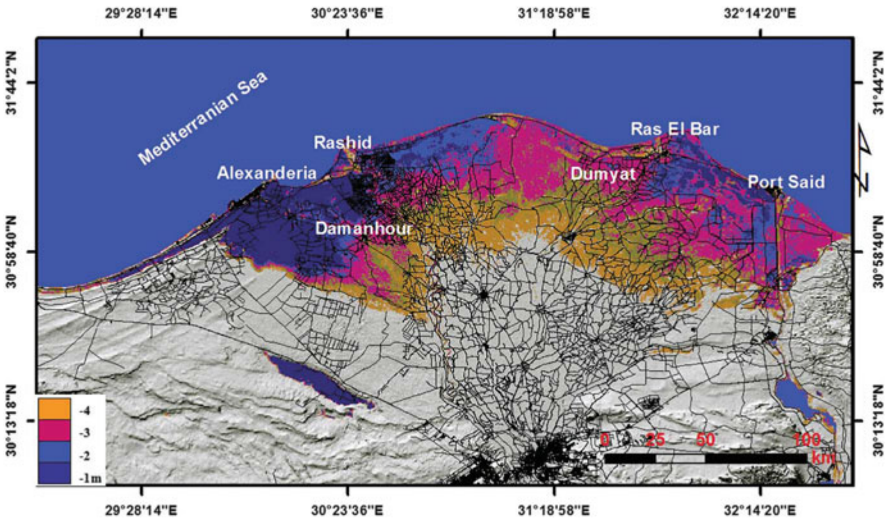

Fig. 5 The areas of the Nile Delta that affected by seawater intrusion when the groundwater table depletes 1, 2, 3, 4, and 5 m below sea level in the case of the GERD non-failure. The areas of Rashid, Alexandria, and Damanhur are more probable to be affected by seawater intrusion than the areas of Ras El Bar, Port Said, and Dumyat [26]

However, the water released by GERD's saddle dam failure would flow that includes drowning of major towns and villages exposing millions to the dangers of death and relocation [27]. The impact of climate change on the Nile River basin is uncertain, and it is not clear whether the Blue Nile countries will experience a wetter or drier climate. Climate change will have unpredictable effects and both higher and lower levels of precipitation – and hence runoff – must be expected in the future [28]. For instance, the dry scenario claims that with increased temperatures from global warming comes increased evaporation rates and hence less water flow in the Nile River, while the wet scenario claims that the increased condensation from evaporation rates will create increased precipitation upstream in the Ethiopian Highlands causing increased runoff in the Nile River downstream. Furthermore, depending on the climate models used and the variability of data and model, opposing trends may appear as a result [29]. However, in the instance of a wet scenario in the Ethiopian Highlands, which would cause flooding and excessive water flow downstream, the GERD may act as a flood protection barrier and reduce flood damage downstream. Flash floods are quite common along the Blue Nile in Sudan, but the severity and intensity of these floods are likely to increase with climate change.

3.6 Infilling Lake Nasser/Lake Nubia with Sediment

During the annual flood, the Nile carries between 80 million and 130 million tons of sediment to Egypt and North and South Sudan from the Ethiopian Highlands. Some of this is deposited along the flood plain of the Nile in North and South Sudan, but most settle in Lake Nubia (the Sudanese portion of the Aswan High Dam reservoir). The reservoir has a trapping efficiency of 99%, which effectively means that only clay-sized particles in suspension are discharged through the dam. All sand- and silt-sized particles remain in the reservoir. Nearly all sediment buildup is confined to between 350 and 500 km upstream of the AHD. Sediment depth ranges from virtually nothing near the AHD to over 75 m at the Second Cataract of the Nile in North Sudan.

If the dam is hit and destroyed, it means that Ethiopia is not affected; however, Sudan and Egypt will be destroyed, as the water collected behind the dam will head north away from Ethiopia and toward Sudan and Egypt. If the GERD fails for any reason, it would mean a yard for all the dams along the river and the courtyard of Egypt and Sudan. In addition to the huge water that will flow over Sudan and Egypt, it reaps its way all green and dry. The fall of the GERD means the collapse of the AHD.

4 Recommendations to Minimize the Water Scarcity Problem

Since this chapter is intended to recommend solutions to the water shortage problem caused by GERD, a number of management actions and strategies are suggested to secure Egypt's water demands. It will be crucial that a serious mitigation plan must be considered in Egypt to solve the water scarcity problems. These management actions are adapted from published research to provide an integrated solution to the water shortage problem caused by the construction of GERD. The following list is suggested to mitigate and minimize the risks of GERD on Egypt.

4.1 Reducing Evaporation Losses from Lake Nasser

The inadequate water supply and the increased future demand necessitate the importance of the optimum use of water resources, which might be obtained through reduction of water losses. Evaporation loss reduction has received increasing attention because of the increase in water demand and the decrease in water availability. The evaporation loss from Lake Nasser is an influential factor in the Egyptian water budget. The water in Lake Nasser lies between the two extremes of a clear water body and a land surface (desert). The lake is deep over much of its area and is relatively clear, resulting in massive storage of solar energy in a considerably greater volume.

Previous estimates of average annual evaporation from Lake Nasser range from 1.7 to 2.9 m or from 4.66 to 7.94 mm day^{-1} [30]. Most of the previous evaporation studies for Lake Nasser applied conventional methods (ground station data), except Omar and El-Bakry [31] and Sadek et al. [30], who applied the Bowen ratio energy budget (BREB) method, but with very limited data. However, Elsawwaf et al. [32] used to obtain evaporation estimates from Lake Nasser; the BREB evaporation rates ranged from 3.4 to 13.3 mm day^{-1} and averaged 7.22 mm day^{-1}. These values were modified using a correction to the BR parameter value based on the average of the values at Allaqui and Abu Simbel stations. After this correction, new evaporation rates were obtained ranging from 2.5 to 11.2 mm day^{-1} and averaged 5.90 mm day^{-1}. They ranged from 2.9 to 9.1 mm day^{-1} and averaged 5.78 mm day^{-1} at Allaqui station and 1.8–9.8 mm day^{-1} and averaged 5.9 mm day^{-1} at Abu Simbel station.

Water loss from the reservoir due to evaporation is between 10 and 16 billion m^3 every year [24]. The wide range is because evaporation volume is a function of the surface area of Lake Nasser/Lake Nubia. Further research on ideas such as a pontoon framework and circular foam sheets is being performed. Another idea is to partially or fully disconnect some of the secondary channels (khors) that do not contribute appreciably to the storage capacity of Lake Nasser due to their shallowness but highly contribute to evaporation from the lake due to their high surface area [33]. They recommend disconnecting some of the khors based on their contribution to evaporation.

There are a considerable number of ideas and techniques to reduce the amount of water lost by evaporation from Lake Nasser water surfaces. They can be summarized as follows [34]: changing water levels upstream Aswan High Dam, cultivating special crops on the lake surface, and closure of secondary channels (khors). Applying the technique in which all the water surface is covered is not practically acceptable as the complete coverage of the surface prevents the exchange between air and water, a matter that affects the oxygen demand needed by the aquatic ecology. Another shortcoming is the use of cover sheets with irregular shapes that lead to the overlapping of sheets when the wind speed becomes faster.

The evaporation can be reduced from an open water surface using floating cover sheets. Different geometric shapes (triangular, trapezoidal, square, irregular, circular, and rectangular) for the cover sheets were studied to find the best one, which gives the maximum percent coverage and permits oxygen exchange between air and water. The most suitable shape achieving the maximum coverage and permitting sunlight penetration through the water was the circular one. Different coverage materials were subject to experimentation and comparison as far as their ability to reduce evaporation from open water surfaces and their durability and cost are concerned. These materials were, for instance, the waxen texture sheets, polystyrene, foam, foamed rubber, perlite ore, plastic sheets, poly-laminated plastic, polystyrene beads, and polystyrene rafts. The most suitable material is the foam sheets.

In conclusions, the yearly average of the daily evaporation rate from Lake Nasser is 6.3 mm day^{-1}. The average volume of the annual water loss by evaporation is about 12.5 milliards cubic meter [34]. To save more than 1 million cubic meters of water loss from Lake Nasser, 0.500 km^2 must be covered with circular foam sheets with an efficiency of coverage equal to 90% [34]. The circular foam system can be adjusted such that it has no impact on the passage of sunlight to aquatic life.

4.2 Maximizing the Use of Groundwater Wells and Rainwater in Egypt

In arid and semiarid regions, where water scarcity is almost endemic, groundwater has played a key role in meeting domestic and irrigation demands. Groundwater is an important resource of water that is used for countless purposes. It is employed for public and domestic water supply systems and irrigation, industrial, commercial, mining, and thermoelectric power production purposes. The amount of groundwater in Egypt is 4.80 km^3/year. In many cases and locations, groundwater serves as the only reliable source of drinking and irrigation water. Unfortunately, this vital resource is vulnerable to contamination. The age of groundwater may range from a few years or less to tens of thousands of years or even more. Old meteoric water often occurs in arid areas where most of the groundwater existed during previous climatic periods with higher rainfall. In Egypt, as an example, the groundwater age of Suez Rift Valley is more than 31,000 years [35]. In many regions, massive use of groundwater has been practiced for some time for irrigation. Groundwater mining and the lack of adequate planning, legal frameworks, and governance have opened a new debate on the sustainability of the intensive use of groundwater resources.

Egypt is a very arid country, where the average annual rainfall seldom exceeds 200 mm along the northern coast. The rainfall declines very rapidly from coastal to inland areas and becomes almost nil south of Cairo. This meager rainfall occurs in the winter in the form of scattered showers and cannot be depended upon for extensive agricultural production. This amount (1 billion m^3/year) cannot be considered a reliable source of water due to its spatial and temporal variability [35].

Areas dependent on rainwater in Egypt cover nearly 2.8 million ha (6.7 million feddan). Most of these areas are located along the Egyptian north coast, between Al-Salloum in the west, near the Libyan border, and Rafah in the east, along with the border with the Palestinian territories. Rainfall can be reliably harvested and used in many countries adding some millions m^3/year to the Arab water resources. Detailed records of rainfall and flash floods are needed to better estimate the amount of water and to adopt appropriate water harvesting technology. Rainfall water is discharging into the Nile River through wadis in Upper Egypt during flash flood seasons. Although this amount of water is small compared with the Nile River discharges, it is considerable in the case of heavy rain on the east and west wadis along the Nile River. In the last few years, the importance of flash flood water increased, due to the increase of population density in the major urban areas of Egypt. This has been a serious stress on the quantity and quality of water. The estimated flash flood water, which is discharging into the Nile River, can be used to control the discharged water to the Nile River from the Aswan High Dam, in order to avoid wasting water, especially in the rainy seasons.

The total quantity of flash flood water which discharges into the Nile River during a water year period (August–July 1994–1995) was about 232 million m^3 [36]. The wadis located east of the Nile River contributed flash flood water (221.50 million m^3) more than those located west of the Nile River (10.50 million m^3).

The second reach (Isna-Nag Hammadi) is considered the most contributing reach of flash flood water to the Nile River (142 m m^3), followed by the third (56 m m^3) and fourth (23 m m^3) reaches, while the first reach is the least contributor (11 m m^3). October (129.90 m m^3), November (74.95 m m^3), March (10.59 m m^3), September (9.35 m m^3), and February (6.84 m m^3) are the months of maximum flash flood water, respectively [36].

4.3 Seawater Desalination

New water sources are rarely available in Egypt for irrigation. It is even less likely for this to be provided to potential users in the future for little or no cost. The use of nonconventional water sources has been practiced for a long time in Egypt. An additional option is desalinization, which is being applied in several areas (some coastal towns, islands, remote industrial sites). The desalination capacity in Egypt has grown to some 150,000 m^3 day^{-1} [37]. The water desalination process separates dissolved salts and other minerals from water. Feed water sources may include brackish, seawater, well, surface water (rivers and streams), wastewater, and industrial feed and process waters. There are two major types of desalination technologies around the world, namely, membrane desalination and thermal desalination. The former technology features the use of a special filter (membrane) to produce desalinated water, whereas the latter technique involves the boiling/evaporation of seawater to give off water vapor, which, on condensation, yields salt-free liquid water.

Nonconventional systems are existing in numerous locations in Egypt, but only for small-scale applications. It is now feasible, technically and economically, to produce large quantities of water of excellent quality from desalination processes. The cost of desalinated seawater is decreasing. Desalination of brackish water is even cheaper. Many countries are now considering desalination as an important source of water supply [38].

Another potential water source is coal seam water (CSW). CSW is obtained as a by-product of gas extraction. This water is normally salty water, which should be treated [39]. CSW can be utilized directly for irrigation if it has low salt content, after chemical treatment or processes to remove the salt. Given that treated CSW is available for use in agriculture, a key question must include how irrigators can best utilize it. This may mean taking action on using it for irrigation in their current production system.

4.4 Sewage Treatment and Reusing Irrigation Water

Treatment and reuse of sewage waters are becoming a common source of additional water in some water-scarce regions. Reuse of wastewater may contribute to future water availability than any other means of water supplies. Water recycling and reuse provide a unique and a viable opportunity to increase traditional water supply. Water reuse can help to close the loop between water supply and wastewater disposal. Firstly, properly treated municipal wastewater often is a significant water resource that can be utilized for a number of beneficial purposes, such as agricultural and landscape irrigation. Secondly, discharge of sewage effluent into surface water is challenging and costly as treatment requirements become more severe to protect receiving waters such as rivers, estuaries, and beaches. The volume of drainage water reused for irrigation has planned to reach a value of 8.3 BCM/year by the year 2017. The reuse of domestic and industrial wastewater is estimated to reach about 1.5 BCM/year by the year 2025 [40].

In addition, reuse of sewage waters, when properly managed, has the advantage of reducing environmental degradation. Water treatment requires chemical, physical, and biological processes to remove contamination. The more common processes used in potable water treatment are the chemical and physical processes. Biological processes are primarily used for the treatment of wastewater. Bioremediation is contamination control innovation that utilizes characteristic biota (microscopic organisms and parasites) and their procedures for contamination diminishing. It is a safe and practical process. Organisms can expel heavy metals from polluted water. This process is referred to as bioaccumulation or as biosorption with ease and in an eco-friendly way. The technique utilizes inherent biological mechanisms to eradicate hazardous contaminants using microorganisms and plants, or their products, to restore polluted environments to their original condition [41, 42]. It is an environmentally friendly and cost-effective technique for heavy metal removal/recovery, when compared to the conventional chemical and physical techniques, which is often more expensive and ineffective, especially for low metal concentrations.

4.5 Maximizing Water Use Efficiency

Different factors recommended maximizing the water use efficiency. First, improve the surface irrigation system by converting small field canals from the surface canal to pipes. This will save 42% of water losses due to seepage and evaporation [43]. Second, utilize fixed furrow irrigation system to save more than 35% from water applied which is equal to 0.24 m^3/m^2 [10]. Then the saved water is 9.36 BCM. Third, decrease irrigation losses by using modern irrigation systems such as sprinkler and drip irrigation in newly cultivated land. The efficiency of modern irrigation systems is 75–85%, in average 80%. Fourth, modify the cropping pattern by using low consumptive use crops. Eliminating rice and other water-consuming plants from the crop pattern could save Egypt nearly one BCM of water, annually [13]. One of the strategies which must be used to maximize water efficiency is the establishment of agricultural projects with Nile Basin countries. The establishment of agricultural projects with Nile Basin countries, such as rice cultivation in countries with abundant water, will maximize the water use in Egypt.

4.6 Starting Giant Projects Out of the Narrow Valley and Delta

By 2017, the total water demand is projected to reach about 79.3 billion m^3/year, while the projected water supply will only reach 76.6 billion m^3/year. This represents 2.7 billion m^3/year deficiencies. Egypt must start giant projects out of the narrow valley and delta to the desert such as the "development corridor" project, expanding arable land along the Nile Valley and also maximizing the use of Egypt's land depressions (e.g., Qattara Depression self-sufficiency development, El Farafra Oasis development, the Toshka Depression development, El Bardawil Lake development).

The expected total amount of saved water using all the above strategies equals 40 BCM which exceeds the expected losses caused by GERD [44]. Adopting all or a combination of the suggested management actions and strategies could reduce or eliminate the impact of GERD on Egypt.

5 Conclusions and Outlook

Twofold objectives are the focus of this chapter. The first objective is to evaluate the land resources of Lake Nasser. The soils surrounding Lake Nasser, i.e., Kalabsha, Toshka, El- Dakka, Abu Simbel at the western side of the lake, and Allaqui area on the eastern side, were established because of water action, while wind action is neglected. Wadi soils are heterogeneous and stratified, which is composed of subrounded grains; this may be related to the distance of transportation. The parent materials of these soils are wadi sediments, shales, and Nubian sandstones. Sedimentation in Lake Nasser is estimated to be around 31 billion cubic meters, which is enough to be absorbed over 300–400 years. The silt is not regularly distributed on the lake floor but is mostly accumulated (more than 30 m in 1992) at the site of the second waterfall around the ancient city of Wadi Halfa. The amount of silt deposited is estimated as 109 million cubic meters per year. The sedimentation of the silt can lead to the blockage of a large part of Nasser's Lake around the second waterfall at Wadi Halfa. This may lead to a significant loss of water due to evaporation and leakage. Because the Lake Nasser reservoir is approaching its maximum storage capacity, the depressions west of Lake Nasser in the southwestern desert of Egypt (Toshka Lakes) are used as a natural flood diversion basin to reduce possible downstream damage to the Nile Valley caused by exceptional flooding.

The second objective is to answer the question: Will the GERD affect Lake Nasser? The factors that impact GERD project on AHD are a reduction in the water share of Egypt, reduction in power generated at AHD, increased salinization of Egypt's agricultural lands, increase in seawater intrusion, environmental degradation, and infilling Lake Nasser/Lake Nubia with sediment. Since this chapter aims to propose solutions for the water shortage problem caused by GERD, a number of management actions and strategies are suggested to secure Egypt's water demands and to minimize the water scarcity problems. The actions identified are reducing evaporation losses from Lake Nasser, maximizing the use of groundwater wells and rainwater in Egypt, seawater desalination, sewage treatment and reusing irrigation water, maximizing water use efficiency, and starting giant projects out of the narrow valley and delta. The yearly average of the daily evaporation rate from Lake Nasser is 6.3 mm day^{-1}. The average volume of the annual water loss by evaporation is about 12.5 milliards cubic meter. To save more than 1 million cubic meters of water loss from Lake Nasser, 0.500 km^2 must be covered with circular foam sheets with an efficiency of coverage equal to 90%. The circular foam system can be adjusted such that it does not affect the passage of sunlight to aquatic life. The expected total amount of saved water using all the above strategies equals 40 BCM, which exceeds the expected losses caused by GERD. Adopting all or a combination of the suggested management actions and strategies could reduce or eliminate the impact of GERD on Egypt.

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The Grand Ethiopian Renaissance Dam, Agriculture, and the Rural Poor in Egypt

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Contents

Abstract This chapter seeks to provide an overview of the impacts of the reservoir filling of the Grand Ethiopian Renaissance Dam (GERD) on the rural poor in Egypt. This requires the analysis of the macro and micro level impacts. To determine the macro level impacts and the micro level implications, three scenarios (4, 6, 8 years) are developed. The macro level assessment shows aggregated water and agricultural land reductions and their subsequent effects on crop value, imports, exports, and employment as well as on government's policy to safeguard self-sufficiency in strategic crops. For the micro level analysis, the sustainable livelihood framework is used to outline impacts on farmers (landowners and laborers) in governorates with high poverty rates, in Lower and Upper Egypt. The main governorates' characteristics and farmers' assets (human, natural, physical, social, financial) and their use in the formulation of livelihood strategies to sustain their livelihoods are presented. The chapter shows that the macro analysis alone does not account for

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farmers' strategies dealing with water shortage indicating that the macro level assessment is not sufficient for comprehending dam impacts on the livelihoods of the rural poor and their consequences.

Keywords Agriculture, Rural poor livelihoods, Self-sufficiency, Water shortage

1 Introduction

Population growth pressures and aspirations for economic development have worldwide renewed the interest for the construction of dams. The aim is to use freshwater for irrigation purposes and the generation of clean electricity. Most of the dams under construction are concentrated in the developing countries [1]. Dams have a wide range of impacts including those on the environment, aquatic life, agricultural production, and socioeconomic conditions of communities. However, the construction of large dams on international rivers does not only affect the country within which the dam is constructed, but impacts transcend the boundaries to downstream countries and their communities, especially those depending on freshwater for agricultural production. For example, the Rogun Dam built by Tajikistan to supply it with low-cost energy increases Uzbekistan's dependence on upstream water releases by Tajikistan during the irrigation season [2]. Turkey's dams on the Euphrates – Keban, Karakaya, and Ataturk, with a storage capacity of about 90 BCM – affect the water quality and quantity used in agriculture in Iraq and Syria that in turn impacts rural communities' livelihoods [3].

The construction of the Grand Ethiopian Renaissance Dam (GERD) with a water storage capacity of 74 BCM to generate 6,000 MW of low-cost energy on the Nile River is expected to affect Sudan and Egypt as downstream countries and their rural communities. Water reduction, especially during the dam reservoir filling period, is anticipated to exacerbate water shortage in Egypt and in turn affect agricultural production and the livelihoods of the rural poor.

This chapter is an attempt to provide an overview of the impacts of the GERD reservoir filling on the macro and micro levels in Egypt. Three filling scenarios (4, 6, 8 years) are developed to show how water shortage over these periods is to impact agricultural production and consequently crop value, imports, and exports on the macro level that necessitate government intervention to maintain self-sufficiency in strategic crops. The impact of water shortage as an "external shock" on the livelihoods of the rural poor engaged in agricultural production in governorates with high poverty rates is assessed. For the analysis of the micro level implications, the sustainable livelihood framework (SLF) is used. Governorates' characteristics and farmers' main assets (human, natural, physical, social, financial) and their combined use in the development of livelihood strategies to attain livelihood goals are outlined. These result from the interplay between the farmers' assets and the government's institutional setup and policies [4]. Though the GERD is to affect water quantity and water quality (e.g., salinity), this chapter is only to address its impact on agricultural production and rural livelihoods in Egypt regarding reduced water quantity.

2 The Agricultural Sector and Food Self-Sufficiency in Egypt

Egypt is an agriculture-based country. The agricultural sector has over centuries been responsible for providing food as well as employing the majority of the population. However, the agricultural sector is currently facing many challenges, on top of which is water scarcity.

Egypt is suffering from physical water scarcity, i.e., limited water sources available within its borders and its dependency on an outside water source for more than 90% of its uses [5]. The annual freshwater supply in Egypt is about 64 BCM/year, of which 55.5 BCM are from the Nile River (about 85% are received from the Ethiopian Highlands via the Blue Nile and about 15% from the White Nile),[1] in addition to about 1.3 BCM of rainfall and about 7 BCM of groundwater [6]. Rainfall and groundwater are limited and cannot be depended upon which makes Egypt highly dependent on the Nile River for all economic and service activities. Agriculture alone uses about 80% of the freshwater from the Nile.

2.1 *Importance of the Agricultural Sector*

The agricultural sector plays a significant role in the Egyptian economy. It is contributing 11.3% of total GDP and 13.1% of GDP excluding petroleum in 2014/2015; though decreasing, it continues to grow at a growth rate of 3% [7]. In addition, industries related to agriculture, such as processing, marketing, and input supplies, account for another 16% of GDP [8]. The share of agriculture in exports is also substantial, accounting for about 10.3% of total exports and about 15% of nonpetroleum exports in 2015/2016 [9]. Agriculture is also a key sector since it provides livelihoods for about 50% (50 million) of the population living in rural Egypt. It directly employs about 30% of the labor force – about 7 million people – in addition to the indirectly employed in agriculture-related industries [6].

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[1] In 1929, there was a treaty between Egypt and Britain securing the water share of Egypt and Sudan (that was part of the Egyptian Kingdom) to be about 84 BCM. In 1959, the 84 BCM were divided between Egypt and Sudan, where Egypt received 55.5 BCM and Sudan 18.5 BCM and about 10 BCM were estimated as the annual water loss due to evaporation.

The agricultural land covers about 4% – about 9 million feddan (Egypt 245 million feddan) – of the total land area. The cropping area per year is about 15 million feddan [10, 11], about 7 million feddan are cultivated in the winter and 6 million feddan in the summer and Nili seasons and about 2 million feddan are permanent trees. However, the annual population increase is contributing to a continuous decrease of the per capita share in agricultural land that dropped from 0.29 feddan in 1950 to about 0.10 feddan since the 1990s [6, 12–14] which is one of the lowest in the World [15] and thus affecting food self-sufficiency.

2.2 *Egypt's Food Self-Sufficiency*

Over the past few decades, the Egyptian government has been thriving to achieve self-sufficiency in the strategic crops, such as wheat, sugar crops, and oil crops, and clover to meet increased local food demands [16]. Two strategies are being followed: growing more food and importing the food deficit. Growing more food has been promoted by two main policies – vertical and horizontal expansion, by seeking to increase land productivity in the Nile Valley and Delta and adding new productive land [17].

Therefore, about 3 million feddan of New Lands have been added to the agricultural land area (about 6 million feddan in the Old Lands[2]) through land reclamation over the past 50 years [6, 18]. However, limited water availability affects the potential of reclaiming additional land [19]. Parallel to this, the Egyptian government has adopted different strategies to make sure that farmers cultivate the strategic crops for domestic consumption. In the absence of a mandatory crop rotation,[3] the government uses financial and regulative policies to boost agricultural production to respond to the domestic consumption increase of cereal and sugar crops [13].

These policies have contributed to the increase of wheat yields from 8 million tons in 2009 to 9.6 million tons in 2015 [6] through increasing the cultivated area from about 2.9 million feddan in 2009 to about 3.4 million feddan in 2015 [10]. The government encourages farmers to expand wheat cultivation areas by increasing its purchasing price. The wheat purchasing price per ton increased from LE2,500 in 2012/2013 to LE2,800 in 2013/2014 [20] and reached about LE4,000 in 2016/2017 [21]. Maize yields have increased from about 6 million tons in 2009 to 8 million tons in 2015, covering an area of about 3 million feddan [6]. For farmers, rice cultivation is the most profitable, and thus it reached 5.5 million tons in 2015. It

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[2] Old Lands exist in the Nile Valley and the Delta in contrast to the reclaimed desert land that is called New Lands.

[3] The cancelation of the mandatory crop rotation since the late 1980s and its replacement with a guided crop rotation have allowed farmers to cultivate what they want depending on their own priorities.

dropped from about 6.5 million tons in 2008 due to government restrictions on rice cultivation – due to its high water consumption – through area limitation. The government also intervened to ban its export to maintain local prices [16]. The sugar crops total production – sugarcane and sugar beet – increased from 25 million tons in 2012 to about 28 million tons in 2015, by expanding the sugar beet area to 0.5 million feddan [6]. This was possible through limitations on exports and increased investment in the sector by the construction of new sugar refinement factories that contract farmers for the cultivation of sugar beet.

Livestock is an important component of the agricultural sector representing about 40% of the value of total agriculture production in Egypt in 2013/2014 [22], while the red meat production accounts for about 40% of the total livestock value [13]. It is dependent on irrigated agriculture of crops such as maize, crop residue, and clover due to the lack of natural grazing areas in Egypt [23]. However, water has again become the limiting factor for the vertical expansion policies.

Therefore, on the national level, efficient water management has become a priority. Since the late 1970s, the Egyptian government has implemented water management projects to improve the main canals (primary and secondary) and the tertiary (mesqa) and quaternary (marwa) canals. These programs seek to improve the infrastructure, establish an integrated approach for water management, and involve irrigation water users [24]. Other programs have also been introduced for the improvement of on-field water management through, e.g., precision land leveling and short cycle crops [16].

Furthermore, to close the food deficit gap, Egypt has been importing about 40% of its cereals. The cereal imports have increased from 10 million tons in 2012 to about 16 million tons in 2015. Wheat imports increased from about 7 million tons in 1998 to 9.4 million tons in 2015. Maize imports increased from 6.8 million tons in 2012 to about 8 million tons in 2015 [13, 25]. Though oil crops production increased by about 15%, about 30% of edible oils are imported [6]. Food imports allow Egypt to maintain food security. However, dependence on international food markets or what is called "virtual water" to mitigate water scarcity [26] entails a twofold risk for Egypt. First, Egypt's reliance on international food markets showed its bad side in 2008 when the main grain-producing countries countered a decrease in their production that limited the available supply on the international market. This, in turn, caused a sharp rise in food prices that negatively affected Egypt's national budget ([27]: p. 2245), especially since wheat/bread is subsidized [20].

Water reductions – during the reservoir filling of the GERD – are expected to severely affect the agricultural sector, increase domestic food shortage, and affect the livelihoods of the poor in general and that of the rural poor in particular: the farmers. In 2012/2013, the highest percentage of poverty was among those working in the agriculture and fishing sector reaching 36.3% compared to 29.1% in 2008/2009 [25, 28, 29].

3 The GERD Reservoir Filling Scenarios and Macro–Micro Implications

The reservoir filling of the GERD – with a storage capacity of 74 BCM – is expected to impact water availability and agricultural production in Egypt. However, the severity of the impacts is to vary depending on the number of filling years assuming that the annual reductions are to be only deducted from Egypt's annual share from the Nile River, the 55.5 BCM.

To this end, three GERD filling scenarios were chosen to identify impacts on Egypt: 4-year, 6-year, and 8-year scenarios. The three scenarios were developed by dividing the total GERD storage capacity – 74 BCM – over the scenario years and then deducting the yearly filling amount from the 55.5 BCM. Accordingly, Scenario 1 decreases Egypt's annual water share by 18.5 BCM; it receives about 37 BCM annually for 4 years. Scenario 2 makes Egypt endure an annual decrease of more than 12 BCM by receiving about 43 BCM annually. Scenario 3 reduces the annual share by about 9.3 BCM to about 46 BCM (see Table 1). These scenarios assume the regularity of rainfall on Ethiopia's highlands, no climate change, and unchanged water use/consumption by Sudan during the filling periods.

The three filling scenarios consequently cause respective reductions in the water available for agricultural (see Table 2). In this chapter, the focus is on water used for the cultivation of field crops that is about 40 BCM in 2015, accounting for 72% of Egypt total share from the Nile River (55.5 BCM) excluding horticulture and permanent trees. Accordingly, calculations of the scenario impacts were based on a cropping area of about 13 million feddan covering the three seasons: summer, winter, and nili [12]. The determination of the field crop areas and their respective water requirements were computed by using data available in Capmas [12], the Annual Bulletin of Statistical Crop Area and Plant Production 2014/2015, and Mohamed et al. [10], Economic Impacts of Expected Water Resources Decrease on the Agricultural Sector.

The determination of water reductions from water used for field crops was executed by multiplying the agricultural water shares – resulting from the scenarios above – by 72% (percentage of freshwater used for the cultivation of field crops). The multiplication results are as follows: the 4-year scenario reduces water available for field crops from 40 BCM to 26.6 BCM and the 6-year scenario decreases it to 31 BCM, while the 8-year scenario lowers it to 33 BCM. Hence, the 4-year scenario is the harshest as it decreases the water share by 13.4 BCM for 4 years, which is equivalent to about 33% of total water used by field crops. The 6-year scenario reduces the water by about 9 BCM for 6 years that is about 22% of total water. The 8-year scenario lowers water available for field crop cultivation by about 7 BCM for 8 years, which equals about 17% (see Table 2).

Water reductions have far-reaching impacts on the macro and micro levels that are addressed in the following sections.

Table 1 Filling scenarios and total water reduction

Scenario years	Annual water reduction in BCM by scenario	Water received by scenario
4	18,500,000,000	37,000,000,000
6	12,333,333,333	43,166,666,667
8	9,250,000,000	46,250,000,000

Table 2 Field crop water share reductions by scenario

Scenario years	Water available for field crops in BCM	Water reduction from water available for field crops in BCM	% of water reduction from total water available for field crops
4	26,640,000,000	13,360,000,000	33.4
6	31,080,000,000	8,920,000,000	22.3
8	33,300,000,000	6,700,000,000	16.8

Source: Calculated by the author using Capmas [12] and Mohamed et al. [10]

3.1 Impacts of Water Shortage on the Macro Level

In the 1950s, the Egyptian government adopted the food self-sufficiency[4] policy; however, its inability to cope with the ever-increasing population growth made it replace the food self-sufficiency policy with the food security policy. Nevertheless, food self-sufficiency has gained increased attention since the 2008/2009 due to the international food crises [30]. Therefore, the Egyptian Sustainable Agricultural Development Strategy in 2009 has put food self-sufficiency in the strategic crops as a major priority (as described in Sect. 2). This chapter assumes that the Egyptian government would pursue the same strategy of prioritizing the cultivation of strategic crops under the three GERD filling scenarios to reduce the need for foreign currency crucial for their imports as well as limit dependence on the fluctuations of the international food markets. Hence, the government's decision for choosing a field crop to be cultivated is based on whether it is a strategic one.

In Table 3, field crops are grouped into crop groups: cereals, sugar crops, oil crops, pulses, medicinal herbs, vegetables, clover, and cotton. The calculation of the percentage of land in feddan, crop water requirement in BCM, and value of crop and crop imports and exports in Egyptian pounds is made by dividing each crop area by total field crop area, by total water consumed by field crops, and by total value and total field crop imports and exports, respectively. The percentage of working days are computed by multiplying crop area in feddan by required working days per feddan (see Table 11 in Annex for working days per crop) and then dividing it over total field crop working days. The percentage of affected

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[4] The FAO (1999) definition of food self-sufficiency is: "The concept of food self-sufficiency is generally taken to mean the extent to which a country can satisfy its food needs from its own domestic production." In contrast, food security does not differentiate between imported food and food cultivated domestically ([30]: p. 89).

Table 3 Overview of field crops by crop group in 2015

Crop group	% of land in *feddan*	% of value of crop in LE	% of crop water requirement in BCM	% of imports in LE	% of exports in LE	% of self-sufficiency	% of working days	% of landowners
Cereals	58.3	46.2	58.4	70.8	6.6	59.9	55.1	58.28
Sugar crops	6.7	8.4	13.7	0.5	21.3	100.0	8.3	6.7
Oil crops	2.2	2.1	2.3	14.6	5.1	70.0	2.0	1.7
Pulses	0.7	0.6	0.4	7.4	2.4	47.8	0.6	0.7
Cotton	1.8	0.9	2.5	2.8	10.3	100.0	2.8	1.84
Medicinal herbs	0.6	0.5	0.3	2.1	3.7	40.0	3.6	0.58
Vegetables	18.0	24.8	12.8	1.5	50.6	111.3	27.3	18.0
Berseem (clover)	11.7	16.5	9.5			100.0	3.4	11.7
Total crop groups	100	100	100	100	100		100	100

Source: Calculated by the author based on Capmas [12] and Mohamed et al. [10]. Cereals include wheat, barley, rice (at the limit of 1.2 million feddan as planned in [16]), and maize; sugar crops include sugarcane and sugar beet; oil crops include peanut, sesame, flax, sunflower, and soya beans; and vegetables include vegetables, potatoes, sweet potatoes, onion, and garlic landowners is determined by dividing the area by crop over the average national landholding size, which is 1.6 feddan[5] and then over total field crop land ownerships.

Based on Table 3, the strategic field crops constitute the following:

1. Cereals cover about 58% of the field crop area and use about 58% of the water available for field crops. Egypt's self-sufficiency in cereals is about 60%; however, its imports account for about 70% of the total field crops' imports, while its total exports are about 7%. To maintain the self-sufficiency rate, an annual increase of about 20% of imports is necessary to cope with the growing local demand [13]. The cultivated cereal area is owned by about 58% of field crop landowners and makes about 55% of the total working days available for farmers.
2. Sugar crops cover about 7% of the total field crop area and consume about 14% of the water. Self-sufficiency in sugar crops is 100%, and exports account for 21% of total field crop exports. However, the maintenance of the self-sufficiency rate requires an annual increase of about 5% of production [13]. For the cultivation of sugar crops, 8.3% of total working days are required. Agricultural land used for the cultivation of sugar crops is owned by about 7% of total field crop landowners.
3. Oil crops cover 2.2% of the land area and consume 2.3% of the water. Self-sufficiency in oil crops is 70%, but to maintain it an annual increase of 5% is needed [13]. Imports account for about 15% and exports for 5%. The percentage of working days made available by the oil crops is 2%, and the area cultivated with oil crops is owned by about 2% of landowners.
4. Clover covers about 12% of the total field crop area and consumes 16.5% of the water. Self-sufficiency is 100%, and it is not part of exported and imported crops. Clover is a low-labor crop as it only requires 3.4% of the total working days while covering land owned by about 12% of the landowners.

The application of the water reductions of 33%, 22%, and 17%, respectively – based on the three scenarios – results in the following combinations of cultivated field crops by scenario (see Tables 3 and 4):

Scenario 1 limits the selection of crops to cereal crops, oil crops, and 50% of the sugar crops that use 67.6% of the water causing a yearly reduction of the field crop cropping area by about 36.5%. It reduces exports by about 90%, including sugar crops (total quantity of sugar crops is used to satisfy local demand), vegetables, cotton, medicinal herbs, and pulses. It affects livestock production due to the noncultivation of clover, as well as self-sufficiency in vegetables, pulses, cotton, and medicinal herbs, which increases imports. It affects farmers' agricultural

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[5] In Egypt, agricultural landholdings are characterized by small land holdings. Landownerships of less than 3 feddan (about 1.2 ha) account for about 85% of farms [6]. The average size of landholdings decreased from 2.7 feddan in 1989/1990 [31] to 1.6 feddan in 2015 [6].

Table 4 Crop groups selection under the three scenarios based on percentage of water requirement

Crop group	Scenario 1: % of crop water requirement	Scenario 2: % of crop water requirement	Scenario 3: % of crop water requirement
Cereals	58.4	58.4	58.4
Sugar crops	6.8	13.7	13.7
Oil crops	2.3	2.3	2.3
Berseem (clover)	0.0	3.2	9.5
Total	67.6	77.6	83.9

Source: Computed by the author based on Table 3

income by reducing the percentage of working days by about 40%[6] and affecting about 36% of landowners.

Scenario 2 allows the cultivation of cereals, sugar, and oil crops in addition to 1/3 of the clover area that together use 77.6% of the water reducing the cropping area by about 29%. Export losses under this scenario are about 67%, including vegetables, cotton, medicinal herbs, and pulses. It still affects self-sufficiency in clover, pulses, cotton, medicinal herbs, and vegetables. It reduces the working days by about 33% and affects about 29% of landowners.

Scenario 3 facilitates the cultivation of cereals, sugar and oil crops, and clover that use 83.9% of water available for field crops, while still reducing the total field crop cropping area by about 21%. Export losses remain at 67% since clover is not part of the exported field crops. The decrease of self-sufficiency in pulses, cotton, and medicinal herbs and vegetables remains that in turn increases imports. Working days available for agricultural laborers are reduced by about 31%, and about 21% of landowners are impacted.

Furthermore, the three scenarios decrease the national revenues from field crops' production by 47.5%, 38%, and 27% (amounting about 9, 7, and 5 billion US$[7]), respectively, and in turn their contribution to GDP. The reduction of agricultural production negatively affects industries depending on locally produced agricultural crops and thus increases imports, as well as local food and fodder prices. Moreover, leaving fertile land fallow reduces agricultural employment (about 4 million, 3 million, and 2 million job opportunities lost by scenario, respectively[8]) and directly affecting livelihoods of landowners' families (about 6.5 million, 5 million, and 4 million people[9] by scenario, respectively) and reducing laborers' working days

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[6] The quantity of working days is computed by dividing the cost of labor by the daily wage based on data from [32].

[7] Based on 2015 prices and exchange rate of 1$ = LE7.5.

[8] Multiplying the number of land left fallow by 1.7 (1 direct job and 0.7 indirect job lost by the loss of one feddan), see El-Hefnawi [33].

[9] Multiplying the number of affected landowners by the average household size, 4.4 members per family [6].

(by about 140 million, 120 million, and 110 million working days, respectively), thus contributing to the eruption of unrests and the increase of crime levels.

The following section is set out to explain how the three scenarios affect the rural poor (agricultural landowners and laborers) in governorates with high poverty rates.

3.2 Impacts of Water Shortage on the Micro Level

In this section, the scenarios are applied to governorates suffering from high poverty rates and have high agricultural employment covering the main regions: Lower, Middle, and Upper Egypt. These governorates are Daqahlia, Sharkia, Kafr El-Sheikh, Gharbia, Menufia, and Beheira in Lower Egypt;[10] Fayoum, Beni Suef, and Minia in Middle Egypt;[11] and Assiut, Sohag, Qena, and Aswan in Upper Egypt. They account for 80% of the total field crop area and are responsible for the production of about 70% of cereals, 50% of oil crops, 80% of sugar crops, 80% of clover, 60% of vegetables, and 60% of pulses in Egypt.

In Table 5, the percentage of the affected field crop cropping area is determined by dividing area by total cropping area by governorate. The percentage of the number of working days is computed by multiplying crop area in feddan by working days per feddan by governorate.

The application of the government's policy concerning strategic crops cultivation based on the three water reduction scenarios – 33%, 22%, and 17% – affects governorates differently based on their cropping pattern (see Tables 5 and 6).

Scenario 1 affects Beheira, Gharbia, and Menufia the most by leaving a high percentage of their land fallow, 43%, 40%, and 39.5%, respectively, because of areas cultivated with clover and vegetables (see Table 5). The percentage of affected landowners is highest in Kafr El-Sheikh, Fayoum, and Daqahlia with 45%, 33%, and 33%, respectively.[12] Affected landowners in Beheira governorate account only for 22% due to the relatively large average landholding size of 4.2 feddan (see Table 7 in Annex for average landholding size by governorate). Laborers affected, in terms of reduced working days, are highest in Beheira, Kafr El-Sheikh, and Aswan with about 47%, 43%, and 39%, respectively, because of their cultivation of labor-intensive crops: cotton, sugar crops (sugar beet in Beheira and Kafr El-Sheikh and sugarcane in Aswan), and vegetables.

Scenario 2 impacts Beheira, Gharbia, and Menufia the most by reducing the cultivated area by 36.5%, 33%, and 32.5%, respectively, mainly because of areas

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[10] Damietta, Qalyubia, and Giza in Lower Egypt have a low agricultural engagement percentage of about 10% and thus are not included in the analysis.

[11] For simplification purposes, these governorates will be treated as part of Upper Egypt governorates in the analysis in the following sections.

[12] The percentage of affected landowners are identified by dividing the land area per crop per feddan over the average landholding size by governorate and then over total field crops by governorate (see Table 7 in Annex for average land ownership by governorate).

Table 5 Cropping pattern by governorate

Governorate/% of crop group	% Cereal area	% Sugar crops area	% Oil crops area	% Clover area	% Cotton area	% Medicinal herbs area	% Vegetables area	% Pulses areas
Daqahlia	62.6	7.6	0.2	15.2	2.6	0.0	11.2	0.3
Sharkia	62.9	4.6	2.9	10.9	2.3	0.0	15.9	0.3
Kafr El-Sheikh	54.4	15.4	0.2	12.7	5.2	0.1	10.7	0.6
Gharbia	58.2	2.7	0.4	16.7	1.7	0.2	19.9	0.1
Menufia	60.3	0.2	0.1	20.7	0.3	0.1	18.3	0.0
Beheira	53.7	3.3	1.4	14.4	4.8	0.2	21.7	0.3
Beni Suef	67.4	6.0	2.7	7.1	0.8	2.3	13.7	0.0
Fayoum	66.1	4.8	0.8	15.3	2.3	2.2	8.5	0.1
Minia	65.6	7.1	5.3	10.9	0.0	1.5	9.4	0.0
Assiut	81.0	1.3	1.0	10.7	0.3	0.8	4.3	0.3
Sohag	75.4	2.4	1.0	15.4	0.1	0.0	5.5	0.1
Qena	55.3	34.7	0.3	5.0	0.0	0.2	4.4	0.0
Aswan	46.4	35.7	2.9	3.9	0.0	3.5	6.9	0.4

Source: Calculated by the author based on Capmas [12]

Table 6 Overview of the impacts on agricultural land, landowners, and laborers in the governorates considering the three scenarios

Scenarios	Scenario 1			Scenario 2			Scenario 3		
Governorate	% Area reduction	% of landowners affected	% reduction of working days	% Area reduction	% of landowners affected	% Reduction of working days	% Area reduction	% of landowners affected	% Reduction of working days
Daqahlia	33.1	32.9	33.5	24.2	22.5	27.3	14.1	20.4	22.8
Sharkia	31.6	28.2	35.6	25.7	21.9	32.1	18.5	20.6	29.2
Kafr El-Sheikh	37.0	45.2	42.7	25.1	29.3	33.8	16.7	27.6	30.3
Gharbia	40.0	32.7	38.8	33.0	26.4	34.9	21.9	24.3	30.1
Menufia	39.5	25.7	37.8	32.5	21.2	35.0	18.7	18.9	29.6
Beheira	43.0	21.7	46.9	36.5	18.0	43.6	26.9	16.9	39.8
Beni Suef	26.9	24.5	26.1	21.6	17.9	22.6	16.8	17.0	20.7
Fayoum	30.7	32.9	28.7	23.2	23.7	24.1	12.9	21.4	19.6
Minia	25.5	23.4	24.5	18.3	14.8	18.0	11.0	13.3	15.1
Assiut	17.1	16.7	14.1	12.8	12.6	11.8	5.7	11.1	8.6
Sohag	22.3	19.8	16.5	16.0	13.5	11.9	5.7	11.4	7.4
Qena	27.0	28.2	32.8	7.9	5.1	6.6	4.6	4.6	5.5
Aswan	32.5	27.0	38.9	13.3	7.6	12.4	10.8	7.2	11.6

Source: Calculated by the author based on Capmas [6, 12] cultivated with vegetables. The percentage of affected landowners are highest in Kafr El-Sheikh, Gharbia, and Fayoum, with about 29%, 26%, and 24%, respectively. Laborers from Beheira, Menufia, and Gharbia are affected the most by reducing 44%, 35%, and 35% of working days, respectively, mainly due to reduced vegetables.

Scenario 3 leaves about 27%, 22%, and 19% of the cropping area (land) fallow in Beheira, Gharbia, and Menufia, respectively, mainly because of the vegetable areas. The most affected landowners are from Kafr El-Sheikh, Gharbia, and Fayoum with about 28%, 24%, and 21%, respectively, because of the exclusion of cotton and vegetable areas in Kafr El-Sheikh and Gharbia and vegetable and medicinal herb areas in Fayoum. Working days are reduced the most in Beheira, Kafr El-Sheikh, and Gharbia by about 40%, 30%, and 30%, respectively.

Findings show that the three scenarios affect some governorates more than others (see Table 6). The cropping area is affected by the type of cultivated crop, while the impact on landowners is determined based on the crop and the average landholding size, while laborers, in terms of reduced working days, are affected by the type of cultivated crop and the work effort required for crop cultivation, i.e., labor-intensive or not.

Based on the above findings, one could presume that the most affected governorates under the three scenarios are Beheira, Gharbia, and Menufia in terms of land reduction; Kafr El-Sheikh, Fayoum, and Gharbia in terms of affected landowners; and Beheira and Kafr El-Sheikh in terms of reduction of working days. This implies that Lower Egypt – especially Beheira, Kafr El-Sheikh, and Gharbia – is affected more than Upper Egypt under the three scenarios.

Nevertheless, the vulnerability of farmers – landowners and laborers – e.g., in terms of reduced agricultural income, depends on their capacities and available resources and their combined use thereof.

4 The Sustainable Livelihood Framework

In this section, the vulnerability of farmers and their ability to cope with the external shock-water shortage are investigated using the sustainable livelihood framework. This includes the identification of farmers' livelihood assets, livelihood strategies, and outcomes [34, 35] (see Tables A1 and A2 in Annex for Governorates' Characteristics and Farmers' Assets).

4.1 Farmers' Livelihood Assets

Livelihood assets are resources that farmers own or have access to that enable them to attain their livelihood outcomes. These are composed of five assets: human assets include farmers' capacities, natural assets refer to access to land and water, physical assets constitute equipment and technologies, social assets address social relations and affiliations, and financial assets contain farmers' capital base [36]. These are detailed below.

4.1.1 Human Assets

The typical agriculture production unit is a small family farm. The household depends on the nuclear and extended family members for the cultivation of the land. More than half of those working for themselves and/or for their families without pay in Egypt are engaged in the agricultural sector and account for about 51.7% in 2012 of total employed in the sector [29]. Croppenstedt [37] established that dependence on agricultural income is positively linked with the household size, i.e., households depending on income as wage laborers have larger households. The average family size in rural Egypt is 4.4. Governorates with the biggest households are Assiut and Qena, with an average of 4.8 members, while the smallest households are in Daqahlia and Gharbia with an average size of 4 members per family (according to 2006 census) [6].

Beheira, Minia, and Beni Suef governorates have the highest labor force engaged in the agricultural sector, with about 55%, 50%, and 47%, respectively, of total employed by governorate, which enables landowners to choose to cultivate labor-intensive crops such as maize, sugarcane, and cotton. The highest female employment is in Beni Suef, Beheira, and Menufia with 52%, 50%, and 50% of their total agricultural employment, respectively. This could be explained by the cultivation of labor-intensive crops that are known to be women's tasks, such as the planting of rice seedlings and the picking of cotton and vegetables and of medicinal herbs [38, 39].

Based on farmers' traditional knowledge, at least two crops are cultivated per year. The main cultivated crops are wheat and clover in the winter season in both Upper and Lower Egypt; however, in the summer season, rice and cotton are cultivated in Lower Egypt and white maize, yellow corn, and sugarcane in Upper Egypt. Small farmers' cropping pattern rests on the cultivation of traditional field crops, including cereals, cotton, clover, and sugarcane. The percentage of cultivated traditional field crops is 82%, while 18% of the cropping area is covered with nontraditional crops (see Table 5). Kafr El-Sheikh and Beheira governorates have the most diversified cropping patterns in Lower Egypt; nontraditional field crops cover about 28% of their total cropping areas, followed by Beni Suef in Upper Egypt where nontraditional crops cover about 25% of its cropping area. The least diversified governorates are Qena, Sohag, and Assiut where nontraditional crops cover about 5%, 7%, and 8% of their cropping areas, respectively. Nontraditional field crops are mainly produced for the market, local and international. In contrast, traditional field crops are mainly used by farming families for subsistence purposes [40], to feed the family and the household livestock, while the excess is traded at the nearest market [41, 42].

Many farmers have become part-time farmers and diversified their income sources. Some farmers are engaged in agriculture and animal-raising activities as well as in nonfarm employment such as being teachers, agricultural engineers, public employees, etc. The annual income sources of households whose head is engaged in agricultural activities in 2015 are divided as follows: agricultural activities contribute about 45% to the total household income that is composed of land-based and livestock-based agricultural income. Another 30% is gained from nonfarm revenues and wages. The remaining 25% comes from transfers, remittances, and rental incomes [43].

4.1.2 Natural Assets

Agriculture in the Old Lands is characterized by small landholdings averaging 1.6 feddan. Most farmers with small landholdings owning less than one feddan practice subsistence farming [44]. Beheira, Aswan, and Kafr El-Sheikh have the highest average land ownerships, 4.2, 2.6, and 2.3 feddan, respectively. Beheira governorate is known to have large-scale agricultural enterprises of reclaimed land, while Kafr El-Sheikh has some of the best agricultural soils. Sohag and Gharbia have the smallest landholdings with an average of 1.2 and 1.3 feddan, respectively, which indicates land fragmentation due to subdivisions as a result of land inheritance.

There are different types of rent arrangements in rural Egypt based on sharecropping or cash. In some villages in Kafr El-Sheikh and Beheira, the common sharecropping arrangements are based on costs and returns of either one-quarter and/or one-half for the sharecropper and three-quarters and one-half for the landowner, respectively. Farmers resorting to sharecropping based on one-quarter are very poor and thus exchange their effort and labor in return for a share of the cultivated crop that is mostly a cereal crop. The cash rent per feddan is determined based on the soil quality or the produced crops [45, 46]. In some villages in Fayoum and Kafr El-Sheikh, cash rents range between LE3,000 and LE4,000 [45]. Only landowners and cash tenants have a say in determining the cultivated crop since they are incurring all the costs, regarding irrigation cost, seeds, fertilizers, etc.

Egypt has a hierarchical irrigation system, composed of different levels of canals: primary, secondary, mesqa, and marwa canals covering the Nile Valley and Delta. Farmers access irrigation water through the mesqa and do not pay the price for the water; however, they pay for the cost of water delivery. Most farmers irrigate their land by lifting the water from canals to their field level through the use of mobile diesel pumps [5], except for some areas where irrigation is by gravity. The use of mobile diesel pumps is widespread in Egypt since the 1980s after the breakdown of the saqia system.[13]

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[13] The saqia system is composed of the waterwheel that is fixed on the canal bank and the saqia ring constituted of farmers responsible for the operation and maintenance of the saqia.

Many farmers at the tail end of canals suffer from water shortage, especially those at the end of the irrigation network in Kafr El-Sheikh and Beheira governorates [47]. In the Nile Delta, farmers access additional water sources by drilling wells [48] or irrigating from drains using their mobile pumps [49].

4.1.3 Physical Assets

Many farmers own mobile diesel pumps that are used for irrigation. However, the average area covered by an irrigation pump differs by governorate. Fayoum and Aswan have the lowest area covered by an irrigation pump, 73 and 44 feddan per pump, respectively. This could be explained by their dependence on gravity irrigation. In contrast, the highest pump area coverage is in Beni Suef and Gharbia, with 7.5 and 7.6 feddan per pump, respectively. Mobile diesel pumps facilitate farmers' access to water from different sources other than their respective mesqa, unlike the fixed saqia.

In some governorates, such as Kafr El-Sheikh, Beheira, and Gharbia, the national irrigation improvement projects have made collective irrigation pumps (operated by diesel or electricity) available in addition to piping the mesqas and marwas.[14] These are stationary pumps operated and maintained by farmers organized in water users' associations. Collective pumps and the piping of mesqas and marwas save water and allow equal water distribution between head and tail-end farmers [24]. However, these stationary pumps have fixed suction hoses or pipes at a certain level, i.e., any change in canal water levels can affect their operation.

The availability of machines for almost all agricultural and irrigation processes has reduced the use of livestock in the field (see Table 8 in Annex for Average Area per Tractor by Governorate). Thus, farmers raise livestock as an important source of income and food [51]. Cows and Nile buffalos produce milk and meat as well as natural manure that is used to improve the agricultural land soil quality. In 2011, about 6% of the Nile buffalos were owned by landless farmers, while about 75% of the Nile buffalos were raised by farmers owning about four feddan [23]. Cows and Nile buffalos' ownership is highest in Beheira and Sharkia governorates with 15% and 10%, respectively [22, 32, 43, 50, 52].

4.1.4 Social Assets

In the 1960s, farmers were migrating to Cairo and Alexandria to work in the booming construction sector, especially farmers from Upper Egypt [53]. Since the late 1970s after the Open-Door Policy, many low-skilled laborers traveled to oil-producing countries. However, in the 1990s, a new wave of migrations commenced; this time the main countries of destination were European countries

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[14] This is done by replacing open canals with buried pipelines.

[54]. Migration and Education through increased exposure have contributed to the change of the social structure in villages and in turn affected social capital, in terms of networks, norms, and trust [45].

Agricultural cooperatives exist in all villages since the 1960s to provide agricultural inputs to farmers; however, their role has gradually declined after the agricultural liberalization in the 1987 and so farmers' dependence on them. In contrast, new organizations have gained status in some governorates, such as in Beheira, Kafr El-Sheikh, and Fayoum: water users' organizations on the mesqa and branch canal levels that are responsible for the operation and maintenance of improved mesqas with collective pumps and for the operation and maintenance of branch canals [55].

4.1.5 Financial Assets

The Agricultural Bank of Egypt[15] is the main source of agricultural financing for small farmers. It provides short-, medium-, and long-term loans to farmers having a registered landholding that is used as collateral [56]. These loans include agricultural activities, regarding financing inputs and equipment, animal breeding, as well as personal loans. Farmers' total loans in Daqahlia and Sharkia in Lower Egypt and Assiut and Qena in Upper Egypt account for about 50% of the total loans in Egypt [50] (see Table 8 in Annex for Loans). According to a World Bank Report [57], most of the loans obtained by poor farmers with small landholdings are used to solve "production bottlenecks" or to finance personal affairs ([57]: p. 22), such as financing the marriage of daughters. In contrast, Helmy [58] states that "marriage cost or health emergencies" are mainly financed through an informal saving and lending mechanism, the rotating savings and credit association (ROSCA) – known in Egypt as "Gamiaa" ([58]: p. 22).

4.2 Farmers' Livelihood Strategies

The three scenarios affect governorates and farmers (landowners and laborers) differently as shown in Sect. 3. However, farming households' strategies to deal with water reductions are based on their assets and on government's policies discussed above. These affect farmers' selection of strategy(ies) followed to attain their goals. Livelihood strategies include agricultural intensification, diversification, and migration [35].

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[15] Law No. 84 of 2016 has recently been promulgated. It states that the Principal Bank for Development and Agricultural Credit (PBDAC) shall be changed to a public-sector bank under the name of Agricultural Bank of Egypt in the form of a Joint Stock Company.

4.2.1 Agricultural Intensification

Farmers would not be willing to leave their land fallow – under the three scenarios – even for one season, especially small farmers which livelihood depends on the agricultural income. They would, thus, seek to maximize the output per unit area through agricultural intensification by increasing the use of agricultural inputs, such as land, water, labor, fertilizers, etc. [59].

Water shortage and water unpredictability would make head farmers over irrigate using their mobile pumps, which reduces water quantities received by tail-end farmers (Holmen 1991 in [17]). In Fayoum, where irrigation is by gravity, water shortage would make farmers resort to water stealing [60] that causes increased infringements on canals. To prevent this from happening, agricultural cooperatives and/or water users' organizations could play a role in monitoring the equal distribution of water among farmers on the mesqa and marwa. However, these efforts might be hindered by the weak social capital that might increase the level of disputes and tension between farmers over irrigation water.[16] This problem is partially countered in Kafr El-Sheikh and Beheira by the improved mesqa and marwa irrigation infrastructure that contributes to water saving and to the equal water allocation between head and tail-end farmers [62–65]. However, water shortage causing low canal water levels would prevent farmers using stationary collective pumps from easily accessing water as well as hinder them from accessing other water sources, such as drain water.

Farmers cultivating nontraditional crops with high net returns – intended for export – would seek access to alternative water sources to maintain their profits, especially those with relatively large landholding size, such as Beheira and Aswan, 4.2 and 2.6 feddan, respectively, that have access to loans. The cultivation of vegetables accounts for about 21% of Beheira's area and 7% of Aswan's total cropping area. Vegetables have a net return per feddan of about 80% of the average farm price. Medicinal herbs in Aswan cover 3.5% of its cropping area (land), and their net return per feddan is about 60% of the average farm price (see Tables A4 and A5 in Annex for Percentage of Field Crop by Governorate and Net Income by Crop). Farmers cultivating these crops are likely to invest in technology to access water, e.g., by the illegal drilling of wells. According to Molle et al. [48], the use of wells is feasible in the southern Delta part as salinity increases in the northern Delta areas (p. 21). Thus, the drilling of wells in the governorates overlooking the Mediterranean Sea, such as Beheira, Kafr El-Sheikh, Daqahlia, and Sharkia, has far-reaching impacts on their soils, as it increases sea water intrusion that leads to the salinization of the fertile agricultural land [66]. To counter this problem under the three scenarios, the government can restrict exports of these crops to discourage farmers from investing in such technology. Nevertheless, the growing local demand would make farmers take the risk.

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[16] In Minia two farmers were killed due to a fight over irrigation priority [61].

In contrast, subsistence farmers with small landholdings who do not take part in the exportation activities – that heavily rely on large producers – are risk averse [16, 67] and do not invest in new technologies. To access additional water sources to cultivate their traditional crops, such as broad beans and clover, they would use mobile diesel pumps either by cooperating with their neighbors or renting additional pumps to irrigate their crops from the drain, especially under Scenarios 2 and 3. Landowners in governorates with high livestock ownership would cultivate clover to accommodate the local demand. These governorates are Beheira and Sharkia in Lower Egypt with about 15% and 10% of total livestock ownership and Sohag and Assiut in Upper Egypt with 7% and 6% of total livestock ownership in Egypt, respectively. This would increase irrigation cost because drains are not always in proximity, thus affecting farmers' incomes. Furthermore, a study conducted on the Meet Yazeed canal flowing through Kafr El-Sheikh and Gharbia governorates found that the use of drain water for irrigation could cause the deterioration of the quality of agricultural land. Depending on the water quality in drains, health risks could also result from such acts [68].

Farmers would also seek to increase the output of land by the extensive use of labor, fertilizers, pesticides, etc. A study conducted in Middle and Upper Egypt found that farmers underutilize fertilizers and pesticides due to their limited supply but instead tend to over utilize laborer to exploit the land intensively [69]. The availability of labor force in Upper Egypt allows the cultivation of labor-intensive crops such as onions, garlic, and medicinal herbs. According to El-Meehy [38], small farmers in Upper Egypt mainly depend on family members in all agricultural activities, while farmers in Lower Egypt depend less on family workers [70] and more on hired laborers. In Lower Egypt, overfertilization negatively affects soils, crops, livestock, and humans [71] as well as water running off to fisheries in the northern lakes [72]. Water shortage would increase the severity of these impacts.

4.2.2 Diversification

Water shortage and low land-based agricultural income would force farmers to seek to diversify their income sources further. They would invest more in livestock breeding, try to access other nonfarm income sources, as well as try to increase their income from renting their assets and/or from family remittances.

Many farmers, especially landless and farmers with less than four feddan, are engaged in raising livestock because it is an important income source in rural Egypt [51].

Water shortage under the three scenarios would encourage farmers to increase their investments in livestock raising, especially due to the high local demand for meat and dairy products by the urban population that is expected to continue in the future [73, 74]. This explains farmers' high share of loans devoted to raising livestock. In 2014, farmers used about 84% of their short-term loans and 43% of their medium-term loans for livestock breeding [50]. A World Bank report [57] states that farmers in Upper Egypt invest more of their resources in livestock production compared to Lower Egypt farmers. However, constraining the cultivation of clover – an important animal feed – under Scenarios 1 and 2 would affect farmers' decisions with that regard.

Landowners would seek to counter this constraint by cultivating clover on their land using drain water, especially in Menufia, Gharbia, and Daqahlia in Lower Egypt and Sohag, Fayoum, and Minia in Upper Egypt that have the largest areas cultivated with clover, covering about 21%,15%, 15% and 15%, 15%, and 11% of their respective field crops' cropping area. These can rent clover field surface to landless farmers to feed their animals. According to Simons et al. [75] in the Nile Delta, some farmers rent their clover fields per unit of surface area to cattle owners with a standard price of LE 125 per qirat (qirat = 175 m^2) in 2012 (p. 22). Increased demand on clover in Lower Egypt would encourage farmers to expand the clover areas on the expense of wheat areas that negatively affect the national self-sufficiency in wheat. This necessitates the government's intervention by increasing the wheat purchasing price and/or by encouraging landowners via agricultural cooperatives to resort to intercropping of wheat and clover [76] to maintain food for farmers' households and their animals [11, 77] as well as safeguard national self-sufficiency. Furthermore, the expansion of livestock raising could encourage farmers to use cereals (wheat and maize) as animal feed [78] in Lower and Upper Egypt. However, in Upper Egypt farmers would rely on the use of maize as animal feed which cultivation is concentrated there, accounting for about 50% of the total maize area in Egypt (see Table 9 in Annex).

Education and government employment schemes adopted since the 1960s have allowed some farming household members to find a job in the public sector. However, since the 1990s, the limitation of public expenditure due to the execution of the Structural Adjustment Program reduced public employment opportunities [79, 80]. Therefore, unemployment is highest among the educated and lowest among those who are illiterate or can only read and write (see Table 7 in Annex). Moreover, employment in privately owned enterprises in rural areas is also limited due to "poor infrastructure, the low diversification in production activities, and the shortage of skilled labor" ([81]: p. 8). This explains the decrease of micro and small enterprise ownerships both in rural Upper and Lower Egypt from about 30% and 27% in 1998 to 14.9% and 18%, respectively, in 2012 [82]. In Upper Egypt, the nonfarm private sector is relatively weak, because of weak demand resulting from low rural incomes. This makes agriculture the main resort for the rural poor – agricultural laborers – who do not have landownership, both men and women, and who lack education [57]. Furthermore, El-Laithy [83] – who conducted a research on poverty in Egypt – states that the rural poor with the lowest expenditure levels are less likely to create their own nonagricultural enterprise and thus continue to work as laborers [83], which applies to farmers in Upper Egypt that suffer from the highest levels of poverty rates (see Table 7 in Annex).

Low profitability of agricultural land would push landowners to subdivide and build on the agricultural land that is to lead to its permanent loss. Currently the annual agricultural land lost to urbanization is assessed at about 20,000 feddan mainly due to soil fertility deterioration in the Nile Delta and Valley [16]. Building on agricultural land does not only affect agricultural production, but it also erodes the bases for agricultural employment and causes the loss of job opportunities. According to El-Hefnawi [33], the loss of one feddan leads to losing one direct job opportunity and about 0.7 indirect job opportunity. Water shortage for longer periods is expected to exacerbate the problem.

4.2.3 Migration

Migration either temporarily or permanently is a means by which some farmers seek to diversify their income to sustain their livelihoods and that of their families. According to McCormick and Wahba [84], the variability of agricultural income can motivate some rural household members to migrate to urban areas to reduce the family vulnerability through income diversification. Migrants usually work in the informal sector, in construction or trade, and send the money they save to support their families [53]. This applies to farmers with large households, such as Qena, Assiut, and Beni Suef that have households composed of 4.8, 4.8, and 4.7 members, respectively (see Table 7 in Annex).

A study conducted in Beheira and Kafr El-Sheikh summarized the reasons that make farmers leave agriculture in the low profitability of the agricultural land resulting from increased production costs and low prices and the unavailability of adequate irrigation water [39]. However, Herrera and Badr [85] provide specific criteria for migration in Egypt. They state that migration is positively linked to education and negatively linked to food availability in rural governorates. Thus, unskilled agricultural laborers lacking education are less likely to migrate, while laborers from governorates suffering from inadequate food production for subsistence use are more likely to migrate.

Accordingly, farmers from governorates such as Minia, Fayoum, and Beni Suef with the highest illiteracy rates on the national level 41.3%, 41%, and 40.5%, respectively, would not migrate and rather continue to work in the agricultural sector. This is confirmed by the high percentage of agricultural engagement in Minia, Beni Suef, and Fayoum with about 50%, 47%, and 43%, respectively. In contrast farmers from governorates with the highest poverty rates such as Assiut, Sohag, and Qena, with 60%, 58%, and 55%, respectively, are more likely to migrate to diversify their income, which corroborates with the findings of Zohry [53]. In Lower Egypt, the average poverty rate is about 18%, and the average illiteracy rate is 31%, compared to 45% and about 37% in Upper Egypt (see Table 7 in Annex). Thus, laborers from Upper Egypt are more likely to migrate than those of Lower Egypt. However, water shortage under the three scenarios would increase poverty rates among laborers and small farmers in Upper Egypt and change conditions in Lower Egypt, which might affect their migration behavior.

The migration of male household members increased the farming responsibilities borne by women and led to the “feminization of agriculture” [39, 86]. However, this does not apply to Upper Egypt governorates where the average of female employment is 23% and the lowest female employment percentage is in Sohag, Aswan, and Assiut with 6%, 13%, and 14%, respectively, of total agricultural employment within each governorate [6], even though laborers from Sohag and Assiut are more likely to migrate as per Herrera and Badr [85]. The explanation for this is that in Upper Egypt, norms and customs do not acknowledge the work of women in the field, except for some women of poor households, who have certain roles in the agricultural production related to harvesting and postharvesting activities [38]. Nevertheless, women in Upper and Lower Egypt would also be affected by water shortage and the decrease of agricultural working days.

Since 2011, political events in the region have made the Egyptian government put restrictions on migration to some Arab countries. Nevertheless, the harsh economic situation has pushed many of the rural youth to seek illegal migration to Europe despite its risk and sometimes devastating ends [87]. In contrast, increased unplanned migration to big cities, such as Cairo and Alexandria, leads to the creation of informal urban settlements [41] that are a cause of many social illnesses. Low land profitability and low agricultural incomes – due to water shortage under the three scenarios – would intensify these problems.

4.3 Farmers' Livelihood Outcomes

The livelihood outcomes are gains reached by farmers (landowners, landless farmers, and laborers) through the livelihood strategies they follow. This section addresses the extent by which farmers are able to achieve one or more of the following objectives under the three scenarios: (1) sustained access to enough food and fodder for the household, (2) access to more income from the agricultural land or from their work, (3) reduced vulnerability, (4) improved well-being, and (5) sustained use of natural resources.

Under the three scenarios, landowners in Lower and Upper Egypt, whose agricultural land is located on the head of a canal, access more water in the absence of strong social capital, which negatively affects tail-end farmers and their incomes and causes the wastage of the natural resource (water). Farmers owning land in areas with collective irrigation pumps in some governorates in Lower Egypt enjoy equal water distribution between head and tail-end farmers. These would feel more secure in their livelihoods; however, low canal water levels due to water shortage under the three scenarios prevent these landowners from accessing alternative water sources, thus affecting their vulnerability.

Under Scenario 1 the cultivation of high return and subsistence crops in Lower and Upper Egypt enables some landowners to achieve crop self-sufficiency and maintain or increase their income by accessing alternative water sources (wells and drains) as well as via the use of laborers and fertilizers. Under Scenarios 2 and 3, the number of landowners accessing alternative water resources for the cultivation of clover would decrease compared to Scenario 1. However, the use of saline water from wells and drains and the unavailability of adequate freshwater – necessary to leach salinity and fertilizer residue – for a long period (6–8 years) are to impact soil quality hazardously and in turn affect land productivity in the long run. Landowners in Lower Egypt would suffer more from soil deterioration because of their location at the end of the irrigation network and due to their proximity to the Mediterranean Sea. Hence, under Scenarios 2 and 3, landowners in Lower Egypt are affected more than those in Upper Egypt, as they are unable to sustain the natural resource base, in terms of agricultural land that might encourage them to build on it.

Farmers in Lower and Upper Egypt have access to loans from the Agricultural Bank that allow them to invest in livestock raising. However, under Scenario 1 farmers have to endure limited clover supply due to cultivation constraints that would encourage some landowners to cultivate clover using drain water or the use of cereals as animal feed. Thus, the expansion of livestock breeding under Scenario 1 would be more in favor of landowners cultivating clover and cereals, in terms of income increase and enhancement of their well-being, while affecting the national self-sufficiency. Under Scenarios 2 and 3, the clover supply would increase by the partial and total removal of cultivation restrictions, respectively, that would be in favor of cattle owners, as well as in favor of the national self-sufficiency in cereals.

The cultivation of high return and subsistence crops by landowners using alternative water resources and agricultural intensification can partially compensate for some of the reduced working days. However, under the three scenarios, many laborers are confronted with high variability in their agricultural incomes, limited access to alternative nonfarm income sources, and restricted migration. Therefore, laborers are unable to secure the subsistence food and fodder for their households and animals. This negatively affects their vulnerability, especially since laborers working in the agriculture and fishing sector spend more than 45% of their income on foodstuff [52]. Spending about half of their income on foodstuff makes farming households vulnerable to income variations and food price increase, especially in Upper Egypt where about 74% of all households suffer from chronic food insecurity [81].

5 Conclusions and Recommendations

The assessment of the impacts of GERD filling on Egypt under the three scenarios showed that water shortage severely impacts agricultural production and the Egyptian economy as a whole, as well as affects the local farming communities. The macro level impacts include land left fallow, trade imbalance and national budget deficit, and the increase of unemployment among agricultural laborers. The assessment of the impact of water shortage on the rural poor on the micro level showed that impacts vary between governorates and within governorates – between landowners and laborers. It also determined that impacts under the three scenarios affect Lower Egypt more than Upper Egypt.

However, the use of the SLF allowed the demonstration of the different practices and strategies pursued by the rural poor to maintain their livelihoods depending on the harnessed assets, which established that vulnerability of laborers from Upper

Egypt is affected the most under the three scenarios. Furthermore, the analysis showed that the livelihood strategies followed by farmers have a bearing on the national food self-sufficiency, national budget, social stability, as well as the viability of the natural resource base: agricultural land.

Hence, these strategies need to be accounted for in any impact assessment as the neglect thereof would among others exacerbate the following:

- Deterioration of agricultural land fertility by the illegal irrigation from drains and the drilling of wells.
- Increased building on agricultural land, which would cause its permanent loss and decrease job opportunities.
- The use of cereals, especially wheat as animal feed, affecting the national food self-sufficiency.
- Increased farmers' dissatisfactions could fuel disputes over access to irrigation water and lead to widespread unrests.
- Loss of agricultural jobs would fuel unplanned internal migration causing many social illnesses, while the illegal migration to Europe contributing to the loss of many lives.

Therefore, the assessment of dam impacts on the agricultural production should not be limited to macro aggregated impact assessment but should be complemented by an examination of the impacts on the rural poor. This would help account for the micro implications as well as consider mitigation and adaptation strategies to improve farmers' resilience to water shortage conditions as well as sustain national resources.

Annex

Table 7 Governorates' characteristics and livelihood assets

Governorate	% of poverty in 2012/2013	% of Illiteracy in 2006	Average family size in rural areas 2006 census	% Male agricultural employment in 2014	% Female agricultural employment in 2014	% of employed in agriculture of total employed (15+ years) in 2014	Average landownership in feddan 2009/2010	% Unemployment of Illiterate and read and write 2014	% Unemployment of lower than intermediate and intermediate 2014	% Unemployment of upper than intermediate and lower than university and university and above 2014
Daqahlia	14.0	27.9	4.0	77.1	22.9	28.2	1.7	12.3	45.9	41.8
Sharkia	14.0	32.1	4.3	76.7	23.3	29.9	1.9	16.7	59.6	23.7
Kafr El-Sheikh	18.0	34.3	4.3	76.8	23.2	43.8	2.3	10.6	63.4	25.9
Gharbia	11.0	25.8	4.0	70.0	30.0	20.2	1.3	9.6	54.5	35.9
Menufia	15.0	27.4	4.2	50.4	50.0	33.6	1.4	10.5	56.4	33.1
Beheira	20.0	36.7	4.4	49.7	50.3	54.7	4.2	18.7	52.9	28.4
Beni Suef	39.0	40.5	4.7	48.5	51.5	46.7	1.6	29.1	49.5	21.3
Fayoum	36.0	40.9	4.6	75.8	24.2	43.3	1.8	33.5	56.4	10.1
Minia	30.0	41.3	4.6	65.6	34.4	49.5	1.7	24.6	55.1	20.3
Assiut	60.0	39.1	4.8	86.2	13.8	33.6	1.5	20.5	52.4	27.2
Sohag	55.0	38.5	4.6	87.1	12.9	33.3	1.2	19.8	58.2	22
Qena	58.0	34.8	4.8	79.4	20.6	34.8	1.6	18.2	61.2	20.3
Aswan	39.0	23.0	4.4	94.2	5.8	30.2	2.6	4	72.4	23.7

Source: Calculated by the author based on Capmas [6]

Table 8 Governorates' characteristics and livelihood assets

Governorate	% of total cows and Nile buffalos in 2014	Average area per pump in feddan in 2013	Average area per tractor in feddan in 2013	% of total loans 2014/15	% of livestock loans (short term) 2014/15	% of agriculture related loans (short term) 2014/15	% of livestock loans (medium term) 2014/15	% of agriculture related loans (medium term) 2014/15	% of agriculture mechanization and transportation loans (medium term) 2014/15
Daqahlia	5.3	39.5	110.9	9.4	94.4	5.6	47.2	38.0	0.0
Sharkia	10.0	12.9	125.0	10.6	99.7	0.3	14.2	0.0	79.7
Kafr El-Sheikh	5.3	11.3	68.3	4.9	95.1	0.7	39.2	51.4	1.0
Gharbia	6.1	7.6	66.8	7.4	83.6	16.4	41.2	39.0	0.0
Menufia	7.2	14.8	96.8	7.2	56.7	43.0	35.2	51.0	2.0
Beheira	15.4	17.5	170.0	6.4	80.7	19.3	55.0	37.3	0.0
Beni Suef	4.6	7.5	133.5	4.9	99.2	0.2	45.7	0.0	5.1
Fayoum	5.5	73.2	165.4	4.6	24.3	73.8	64.8	0.5	2.3
Minia	5.4	12.6	113.5	7.3	95.5	1.0	41.5	4.6	0.8
Assiut	5.7	23.2	95.3	11.0	94.7	4.1	45.4	3.5	3.4
Sohag	6.9	24.8	107.3	4.2	75.8	1.4	72.0	1.3	4.0
Qena	5.5	21.9	82.2	9.2	84.7	15.3	32.8	23.2	5.6
Aswan	1.5	44.2	171.9	1.3	75.9	23.6	19.0	77.6	3.4

Source: Calculated by the author based on Capmas [22, 50]

Table 9 Percentage of cultivated field crops by governorates of total field crop cultivation in Egypt

Governorate	% of total wheat area	% of total barley area	% of total maize area	% of total rice area	% of total oil crops area	% of total sugar beet area	% of total sugarcane area	% of total clover area	% of total cotton	% of total medicinal crops	% of total vegetables	% of total onion	% of total garlic	% of broad beans area	% of lentils, chickpeas, and lupine area
Daqahlia	7.9	0.1	3.7	31.3	0.9	16.7	0.1	11.4	13.0	0.7	5.3	11.24	5.27	7	
Sharkia	12.0	8.9	9.3	18.2	14.5	12.0	0.0	9.7	13.6	0.2	10.4	4.68	3.16	9	33
Kafr El-Sheikh	6.7	2.3	2.4	20.5	0.8	28.0	0.1	7.9	22.0	1.5	5.1	0.62	–	14	
Gharbia	4.3	0.0	3.2	8.9	0.8	2.7	0.4	6.1	4.2	1.8	3.7	21.20	0.92	1	
Menufia	3.9	–	7.3	0.0	0.2	0.2	–	7.3	0.7	0.6	4.9	0.62	0.32	0	
Beheira	10.4	2.7	10.6	13.4	7.4	9.2	0.05	13.7	30.6	3.2	15.3	5.74	2.82	12	
Beni Suef	4.2	0.2	7.7	0.1	5.0	5.8	0.03	2.4	1.8	16.6	2.5	5.62	33.08	0	
Fayoum	6.5	2.0	9.6	0.03	2.1	6.5	0.1	7.2	7.1	21.8	2.6	4.26	6.98	1	
Minia	7.6	1.3	10.2	–	15.6	4.4	11.0	5.7	0.1	16.5	3.2	4.53	13.00	1	15
Assiut	6.5	0.4	9.8	0.001	2.1	1.2	0.4	4.1	0.9	6.4	0.9	3.36	1.75	4	16
Sohag	5.5	0.2	8.6	–	2.1	–	4.3	5.5	0.3	0.0	0.8	6.98	1.42	1	
Qena	3.1	0.3	2.8	–	0.4	–	36.0	1.0	–	0.9	0.6	1.17	0.86	0	2
Aswan	1.9	14.6	1.2	–	2.4	–	26.2	0.6	–	11.0	0.7	0.93	1.45	2	
% of Total Egypt	80	33	86	92.4	54	87	79	83	94	81	56	71	71	52	65

Source: Calculated by the author based on Capmas [12]

Table 10 Percentage of field crops by governorate

Governorate	% of total wheat area	% of total barley area	% of total maize area	% of total rice area	% of total oil crops area	% of total sugar beet area	% of total sugarcane area	% of total clover area	% of total cotton	% of total medicinal crops	% of total vegetables	% of total onion	% of total garlic	% of broad beans area	% of lentils, chickpeas, and lupine area	Total
Daqahlia	22.5	0.0	8.7	31.4	0.2	7.6	0.0	15.2	2.6	0.0	9.2	1.82	0.13	0	0	100
Sharkia	28.8	0.4	18.5	15.3	2.9	4.6	0.0	10.9	2.3	0.0	15.2	0.64	0.07	1	0	100
Kafr El-Sheikh	22.9	0.1	6.8	24.6	0.2	15.4	0.0	12.7	5.2	0.1	10.6	0.12	–	1	–	100
Gharbia	24.7	0.0	15.3	18.1	0.4	2.5	0.2	16.7	1.7	0.2	12.9	6.98	0.05	0		100
Menufia	23.6	–	36.7	0.0	0.1	0.2	–	20.7	0.3	0.1	18.1	0.21	0.02	0		100
Beheira	23.3	0.1	19.7	10.5	1.4	3.3	0.0	14.4	4.8	0.2	20.9	0.73	0.05	1	–	100
Beni Suef	26.4	0.0	40.8	0.1	2.7	6.0	0.0	7.1	0.8	2.3	9.8	2.03	1.82	0	0	100
Fayoum	29.6	0.2	36.3	0.1	0.8	4.7	0.1	15.3	2.3	2.2	7.1	1.10	0.27	0	–	100
Minia	31.0	0.1	34.6	–	5.3	2.9	4.3	10.9	0.0	1.5	7.9	1.05	0.46	0	0	100
Assiut	35.8	0.0	45.2	0.0	1.0	1.1	0.2	10.7	0.3	0.8	3.2	1.05	0.08	1	0	100
Sohag	32.8	0.0	42.5	–	1.0	–	2.4	15.4	0.1	0.0	3.1	2.36	0.07	0	0	100
Qena	31.6	0.1	23.6	–	0.3	–	34.7	5.0	–	0.2	3.6	0.68	0.08	0	0	100
Aswan	27.8	3.8	14.8	–	2.9	–	35.7	3.9	–	3.5	6.0	0.76	0.18	1	–	100

Source: Calculated by the author based on Capmas [12]

Table 11 Net income, and working days per crop

	Crop	% of net income of average farm price per feddan	Working days per crop per feddan
Winter crops	Wheat	45.0	23
	Barley	42.5	17
	Broad beans	27.8	25
	Lentils	62.2	19
	Chickpeas	28.9	21
	Lupine	20.3	19
	Fenugreek	29.2	19
	Clover (Tahareesh)	78.0	14
	Clover (permanent)	77.2	7
	Flax	51.0	17
	Onion and garlic	87.6	15
	Sugar beet	66.2	25
	Medicinal herbs	59.6	25
Summer crops	Rice	34.0	24
	Maize	32.6	34
	Sorghum	44.2	21
	Yellow corn	–	28
	Soya beans	58.3	21
	Peanuts	60.8	28
	Sesame	66.2	25
	Sunflower	42.2	17
	Sugarcane	11.1	49
	Cotton	27.1	42
	Vegetables	79.1	45

Source: Calculated by the author based on Capmas [12] and Mohamed et al. [10]

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Assessment of Sediment Deposition in Aswan High Dam Reservoir During 50 Years (1964–2014)

Ahmed Moustafa A. Moussa

Contents

Abstract During the last century, many dams exist along the Nile River for various purposes. The existing reservoirs especially those on the Blue Nile, Atbara, and the main Nile River are seriously affected by sediment deposition at unexpected rates.

Roseires Dam was constructed on the Blue Nile (Sudan) to store water for irrigation; the dam lost 40% of its original capacity in a span of 43 years. Khashm

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el-Girba Dam was constructed on Atbara River (Sudan); the dam lost 53% of its original capacity in a span of 46 years.

As for the Aswan High Dam (AHD), it created a reservoir behind it which is Aswan High Dam Reservoir (AHDR). The AHDR is the second largest human-made reservoir in the world. The reservoir extends from the southern part of Egypt to the northern part of Sudan. The AHDR has a total length of about 500 km (350 km inside Egypt and 150 km inside Sudan), the average width of the reservoir is about 12 km, and its storage capacity is 162 billion m^3.

This chapter is an attempt to assess and analyzes the deposition in the Aswan High Dam Reservoir during the last 50 years from 1964 to 2014, by using different techniques to estimate the effective life span of the reservoir.

The traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing by GIS method.

Keywords Aswan High Dam, Delta, Deposition, Egypt, GIS, Reservoir, Sedimentation, Sudan

1 Statement of the Problem

Reservoir sedimentation is a worldwide serious problem and considered as a salient enemy. The graduate loss of capacity reduces their effective life span and decreases their irrigation reimbursements, so as the generation of hydropower, water supply, flood control, and navigation clearance under bridges. Also, sediment deposition propagates upstream, up tributaries and ridges. Moreover, it affects water withdrawals and division. Also, they reduce the sediment load downstream, which might result in the channel and tributary degradation, bank erosion, and in changes of the aquatic habits to those more suited to clearer water discharge.

During the last century, many dams exist along the Nile River for various purposes. The existing reservoirs especially those on the Blue Nile, Atbara, and the main Nile River are seriously affected by sediment deposition at unexpected rates. Currently, for some reservoirs, costly sediment control measures are being practiced. The decision of postponing the problem by heightening the dam has been taken, and the unresolved situation is waiting for those in design and planning stage. Also, the Aswan High Dam, though large, is facing the problem of 100% trap efficiency. Further, in Sudan, Ethiopia, and Uganda, new dam projects are underway or have been proposed.

2 Types of Reservoir Sedimentation

Rivers carry sediment particles with different sizes. These particles are transported as a bed or suspended load. Bed load material is of coarse sediment particles that move near the bed and start to deposit at the beginning of the reservoir entrance in the form of the delta as shown in Fig. 1. As for the suspended sediments, they are fine particles with relatively less fall velocity. They are transported deeper into the reservoir either by non-stratified flow forming a uniform deposition at the middle of the reservoir or by stratified flow depositing at the lower part of the reservoir forming a muddy lake. The suspended load is divided into two parts; one comes from the bed of the river, and the other load from the catchments area as wash load.

Batuca and Jordaan [1] have classified the reservoir sedimentation based on the location of deposition into three categories, with the inclusion of the sedimentation in backwater reaches as a part of the reservoir sedimentation. The position of each type of reservoir sedimentation can be seen in the longitudinal profile of the reservoir as presented in Fig. 1 which are classified as backwater deposition, delta deposition, and bottom-set deposition.

2.1 Backwater Deposition

This type of deposition occurs in the river reach before entering the reservoir. After changing the water level in the river by the effect of backwater curve, the velocity of the water will be reduced. Accordingly, a small portion of coarse sediment will settle in this zone and extends into the reservoir to form a delta. Thus forming a transition, separating the riverbed and the delta formation, is evident (Fig. 1). In theory, the backwater deposit should grow progressively, upward and downward. Consequently, bedforms changes occur. However, this growth is limited because the stream adjusts its channel by eliminating meanders, forming a channel having an optimum width-depth ratio, or varying bedform roughness. These factors make the stream transports its sediment load through the reach of evolution done in one direction Nzar [2].

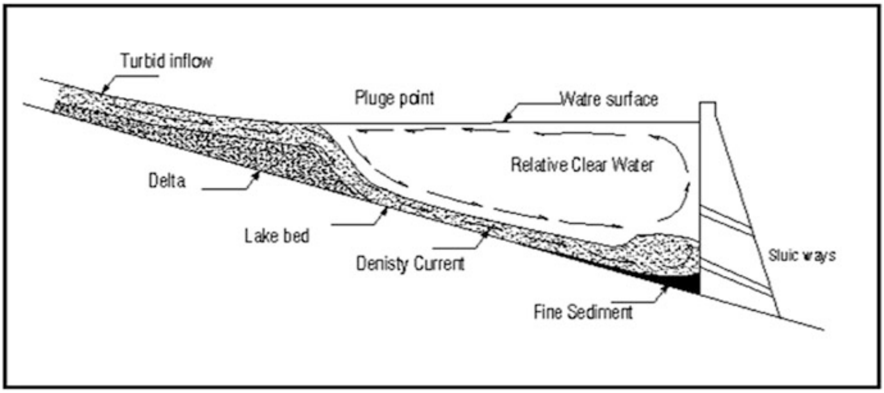

Fig. 1 Longitudinal cross section of reservoir sedimentation

The deposition at the backwater is not stationary, as it fluctuates and advances toward the delta in the reservoir. Accordingly, water surface variation of the reservoir, flow velocity, so as the backwater sediment are carried and transported toward the reservoir and contribute to the formation of the delta.

2.2 Delta Formation

Deltas are formed at reservoir entrances or lake inlets or into the sea. This is achieved by the progressive deposition of large sand sizes (i.e., bed load). This is attributed to the fact that the sediment carrying capacity is reduced.

The water level changes and the expansion of the cross section are the main reasons for water velocity diminishing, and sediment movement is interrupted at the delta zone. Accordingly, deposition occurs at the beginning of the reservoir, where it takes place in the reservoir and basin (i.e., main river zone and over the floodplain) Batuca and Jordaan [1].

Based on the reservoir sedimentation observation, the delta formation contributes to the sedimentation of small reservoirs. On the contrary, large reservoir deltas constitute of a small portion of sedimentation, Morris and Fan [3].

Due to the shallow part small volume at the reservoir entrance, the delta has a relatively smaller volume, which is problematic in terms of upstream aggradation. The cross section of the delta in the longitudinal direction is divided into two zones (i.e., top- and front-set bed) with a different surface slope so as deposition texture as shown by Fig. 2. Strand and Pemberton [4] mentioned that the top-set delta slope ranges between 100 and 20% relative to the original slope that was found at the beginning of the observation. This was the same in 31 observed reservoirs in the States.

For design purposes 50% slope (S) is acceptable. Hence:

$$S\ \text{top set} = 0.5\ S\ \text{river}$$

Based on the same survey data done by Strand and Pemberton [4], the slope of front set can have the relation:

$$S\ \text{front set} = 6.5\ S\ \text{top set}$$

Under some conditions, the delta forms a major part of the sedimentation of the reservoir (i.e., Glenmore Reservoir – Canada). In this reservoir, 10% of its capacity was lost in 1968 with 70% accumulated in the delta zone, Morris and Fan [3].

The delta advances toward the reservoir in different ways. They are influenced by the reservoir geometric shape at its inlet and its hydraulics. This causes different delta propagation and speed, which have different implications on reservoir sedimentation. Sloff et al. [5] documented the parameters affecting the delta formation shape (i.e., valley slope so as for shape and length, sediment size so as distribution, and reservoir operation so as inflow capacity).

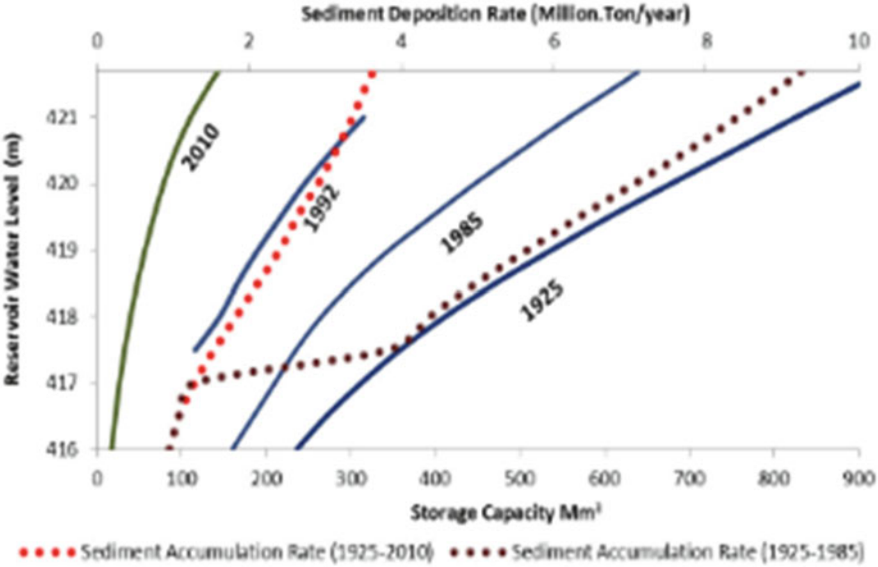

Fig. 2 Reservoir sedimentation and sediment accumulation rate for Sennar Dam Abdallah and Jürgen [8]

The empirical criterion developed by Zhang and Ning [6] mentioned that there are two types of delta formation (i.e., wedge-shaped deposits and delta-shaped deposits). The first has a front that reaches the dam with uniformly distributed sediments, while the second front is away from the dam with nonuniformly distributed sediment.

According to Chang [7] experiments, the delta started with bed load deposition at the mouth. The suspended load is deposited relatively more uniformly over the bottom, Nzar [2].

2.3 *Bottom-Set Bed Depositions*

Bottom deposition is formed by depositing fine sediment, which is transported by water to the reservoir middle and end. This type of fine sediment is composed of clay and silt, which are transported by turbidity currents or by the turbulent suspension. Its deposition starts beyond the delta upstream the dam wall site.

The shape and configuration of the deposit are affected by the process of transporting and depositing of suspended material. There are two main ways of transporting fine sediment into the reservoir body. First, one is by suspension action of the sediment particle. In this case, they travel toward the reservoir by turbulence of water or by small particles electromagnetically. The second way is by gravity action on the sediment-laden water, which enters to the bottom of the reservoir in the form of a turbidity current.

2.4 Depress Flow

Woods and light material that come with flow cause many troubles and interruption during dam operation. They are quite dangerous to gates and especially to running turbines when the protecting screens are broken under the heavy pressure of the accumulated materials. The best method to get rid of depressing is to direct these floating materials toward the spillways to pass downstream. However, since the depress (wood) comes from the upper catchments, then it would be better to treat the problem, thereby improving and protecting the environment of the wood source. For more information on this topic, consult the reference Nzar [2].

3 Sedimentation in Nile Basin

The reservoir storage is used for water supply, irrigation, power generation, and flood control, but in Sudan, creeping problem of sedimentation causes several implications. First, the lost storage capacity has an opportunity cost in the form of replacement costs for construction of new storage since the present level of supply is to be maintained. Second, there are direct losses in the form of less hydropower production capacity available, less irrigated land to produce food, and reduced flood routing capacity. Finally, the fully silted reservoirs created a decommissioning problem that has both direct and indirect costs.

From Figs. 2, 3, and 4 show reservoir sedimentation and sediment accumulation rate for Sennar, Roseires, and Khashm el-Girba Dam, while Fig. 5 shows the sediment-monitoring network in the Nile Basin. On the other hand, Table 1 shows reservoir sedimentation for some dams in the Nile Basin countries.

From Figs. 2, 3, 4, and 5 and Table 1, it can be seen that the reservoir sedimentation is one of the major challenges in the field of the water resources management in the Nile Basin countries. The process of monitoring and calculation of the reservoir sedimentation is very important for the operation rules of reservoirs.

For example, in Roseires Reservoir, regardless of all efforts done by National Electricity Corporation (NEC) and MOIWR, the sediment problems are still growing. The adverse effects of these problems can be reflected on the socioeconomical part to all users of the dam. The average cost of sediment removal may reach more than 626,000 million US$ per year. Currently, the average annual volume of sediment removed from the hydropower intakes is estimated to be 125 M m^3/year at an average cost of 5 US$ per cubic meter.

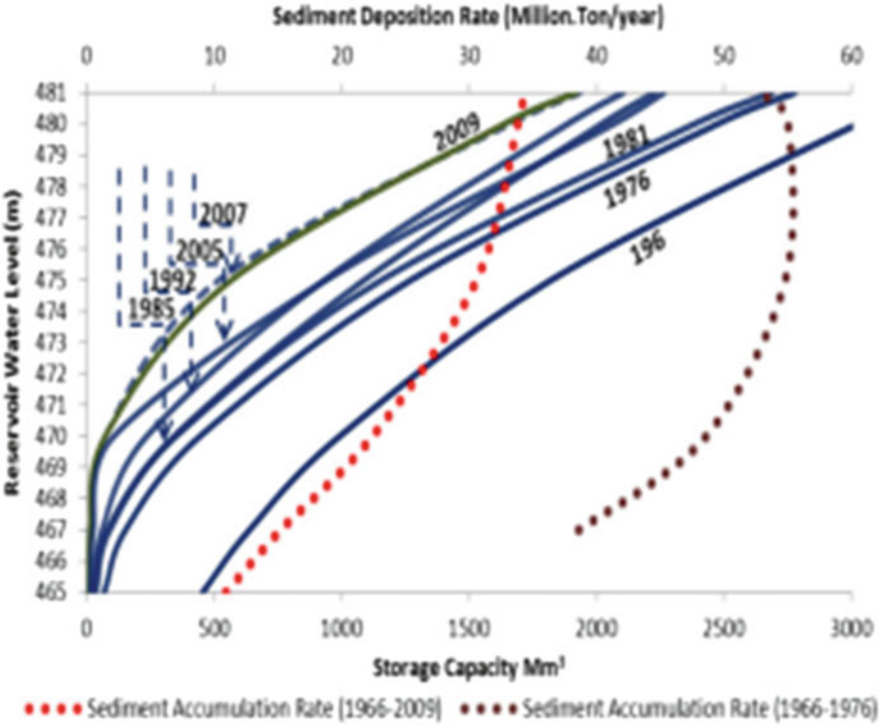

Fig. 3 Reservoir sedimentation and sediment accumulation rate for Roseires Dam Abdallah and Jürgen [8]

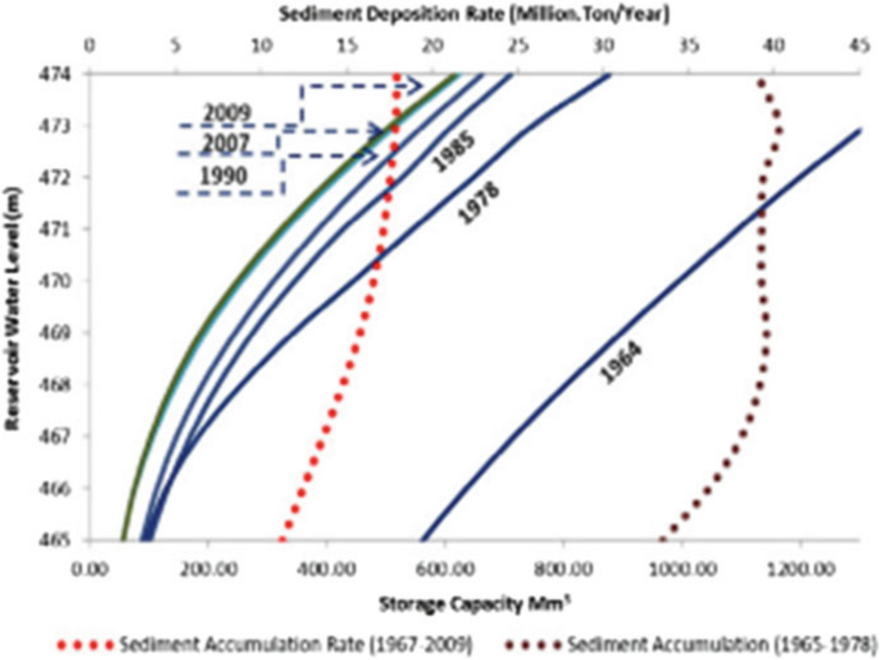

Fig. 4 Reservoir sedimentation and sediment accumulation rate for Khashm el-Girba Dam Abdallah and Jürgen [8]

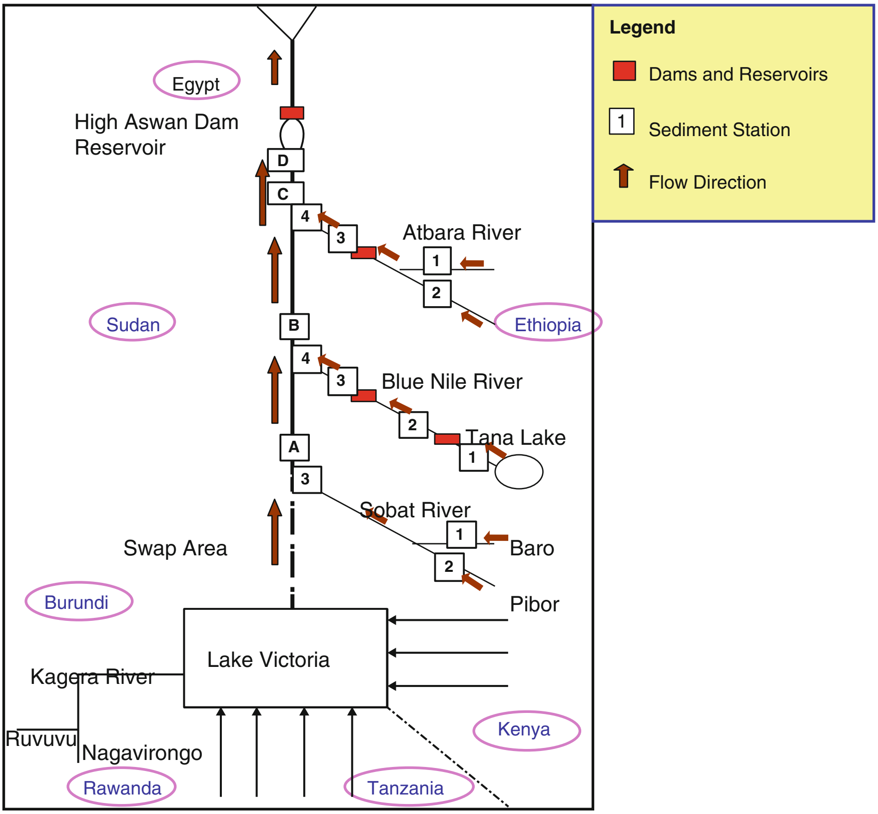

Fig. 5 Layout of the sediment monitoring in the Nile Basin

Table 1 Reservoir sedimentation for some dams in the Nile Basin countries

Reservoir	Country	Name of river	Period considered	Storage losses (%)
Angereb	Ethiopia	Angereb River	1986–2015	46
Koka (Awash R.)	Ethiopia	Awash River	1960–1999	32
Roseires	Sudan	Blue Nile	1966–2009	40
Sennar	Sudan	Blue Nile	1925–2010	85
Khashm el-Girba	Sudan	Atbara River	1964–2010	53
Aswan High Dam	Egypt	Main Nile	1964–2012	4.16

4 The Aswan High Dam Reservoir Sedimentation Rate

The sediment load of White Nile and tributaries is small (i.e., 5% of the annual load of the main river). Meanwhile, 95% of the load is received during the flood and originates from the Ethiopian Plateau.

The Blue Nile system consists of two main tributaries, the Rohad and the Dinder, which join the main stream below Wad Madani (Sudan). These tributaries are fast-

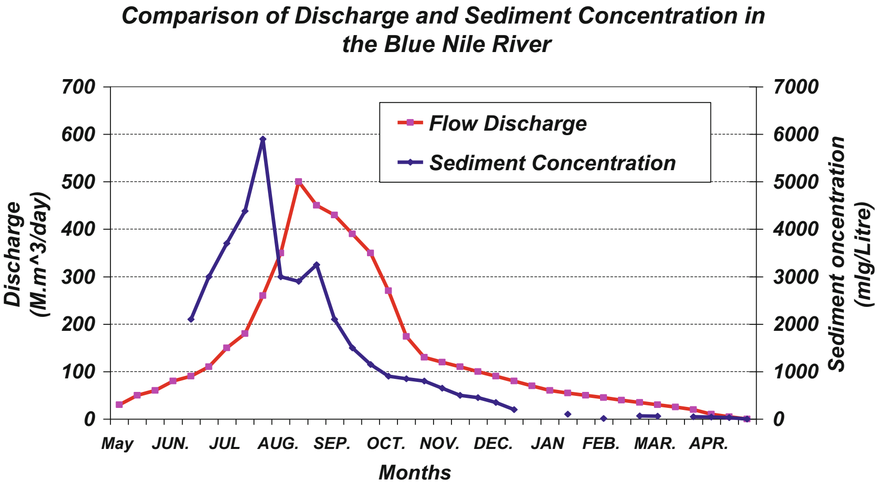

Fig. 6 Comparison of discharge and sediment concentration in the Blue Nile River

flooding stream and drive their water and sediment from the Ethiopian plateau. There are four stations in the Blue Nile, namely, Roseires, Wad Elais, Sennar, and Wad Madani, to measure suspended sediment concentration and flow discharges. The estimated annually suspended load of the Blue Nile was 185 million tons measured at Roseires station (Alexander Gibb 1954). It is noticed that more than 80% of the Blue Nile flow occurs during the period (July–Oct) with a peak in August. The maximum flow may be reached more than 900 M m^3/day; however, during the dry season (Jan–April), the flow may be as low as 10 M m^3/day. The peak of the average discharge comes after the peak of the sediment by about 3 weeks because the sediment is quickly mobilized. This is the characteristic of the Nile Basin catchments. Average sediment concentration is about (4,000 ppm) with maximum values sometimes reaches to (6,000 ppm) as shown in Figs. 6 and 7 [9].

5 Relation Between Discharges and Sedimentation in Aswan High Dam Reservoir

The statistical regression was performed, and the relationship between the flow discharge and sediment discharge can be described by either a linear relationship or a polynomial relationship as follows:

Linear relationship ($R^2 = 0.77$):

$$Y = 0.0011\,X \tag{1}$$

Polynomial relationship ($R^2 = 0.93$):

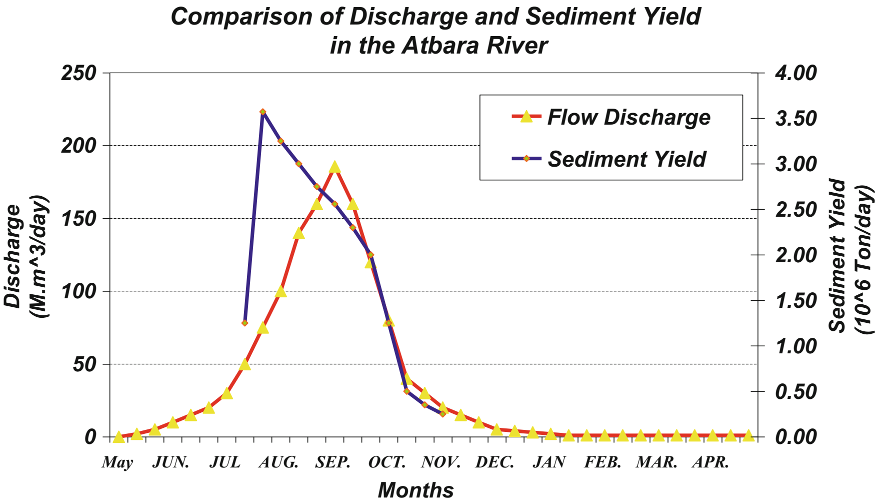

Fig. 7 Comparison of discharge and sediment yield in the Atbara River

$$Y = 6 \times 10^{-10} X^2 - 0.0004X + 70.066 \tag{2}$$

where Y is the total accumulated sedimentation (BCM), X is the total accumulated water discharge (BCM), Aziz and Ismail [10].

6 Previous Sedimentation Studies in AHDR

The literature in the field of reservoir depositions was reviewed. Based on the revision, it was clear that the investigations of sediment deposition in Aswan High Dam Reservoir were concerned with two periods (i.e., pre- and post-1985), e-sciencedirect.

Pre-1985, the investigators were involved in analyzing field data to signpost the reservoir characteristics to designate relationships between sediment and flow. Post-1985, researchers developed mathematical models to the water and sediment to simulate water surface and bed profile (i.e., Hurst [11], Shalash [12], El-Moattasem et al. [13], Abdel-Azez [14], El-Manadely [15], Entz [16], and Smith [17]).

- Hurst [11] found that there was no coarse sand in the reservoir. He documented that 30%, of the sediment, by weight, was transported (i.e., 40% silt and 30% as clay).
- Shalash [12] suggested that the average al rate of sediment was 130 × 10^6 tons, and the average rate of outflow was 6 × 10^6 tons. Accordingly, he documented

that the average sediment deposition was 124×10^6 tons. The deposited sediment was $1{,}570 \times 10^6$ tons through 15 years of observation.

- EL-Moattassem and Abdel Aziz [13] considered the sediment balance in Aswan High Dam Reservoir during May 1964 to December 1985. They calculated the volume to be 1650×10^6 m^3, while the deposited volume from hydrographic surveys was $1{,}657 \times 10^6$ m^3 for the same period.
- Abdel Aziz [14] and El Manadely [15] developed 1-D model based on continuity so as momentum equations and the sediment continuity equation. This model could estimate river bed profile change. They determined the deposited volume to be 2,650 BCM during 1964 to 1988. This is equal to estimated volume from field measurements (i.e., 2,760 billion m^3). They concluded that the Aswan High Dam Reservoir cross sections are irregular in the transverse direction. They suggested that developing a new approach to 2-D models is important to predict sediment deposition in transverse and longitudinal directions.
- Entz [16] in 1977 found that sedimentation had been occurring between km 420 and 290 upstream on the dam with its peak at km 350 through echo sounding the lake bottom as early as 1973. He deduced that the sedimentation peak is gradually moving northward. Moreover, he forecasted that the lake would not be completely filled for 1,700 years. In 1980, Entz reinvestigated the sedimentation processes in Lake Nasser during the period from 1965 to 1974. He deduced that the bulk of suspended silt was deposited around the previous second cataract with a layer of 10–25 m thick.
- The wide range of the estimated lifetime differences may be due to many variables including computation method, data input, and theoretical assumptions dealing with the mathematical approach taken Smith [17].

7 Different Techniques for Calculating Sedimentation in AHDR

This section is concerned with the techniques of calculating morphological changes with a new DTM algorithm.

7.1 GIS Method

GIS method will be used for Sudanese part only, which contains 82% of the total sediment deposit in the AHDR.

7.1.1 Algorithm of DTM

Morphological changes calculation could be predicted if the data is available over time steps. By comparing them to the calculated volumetric changes, the changes could be monitored.

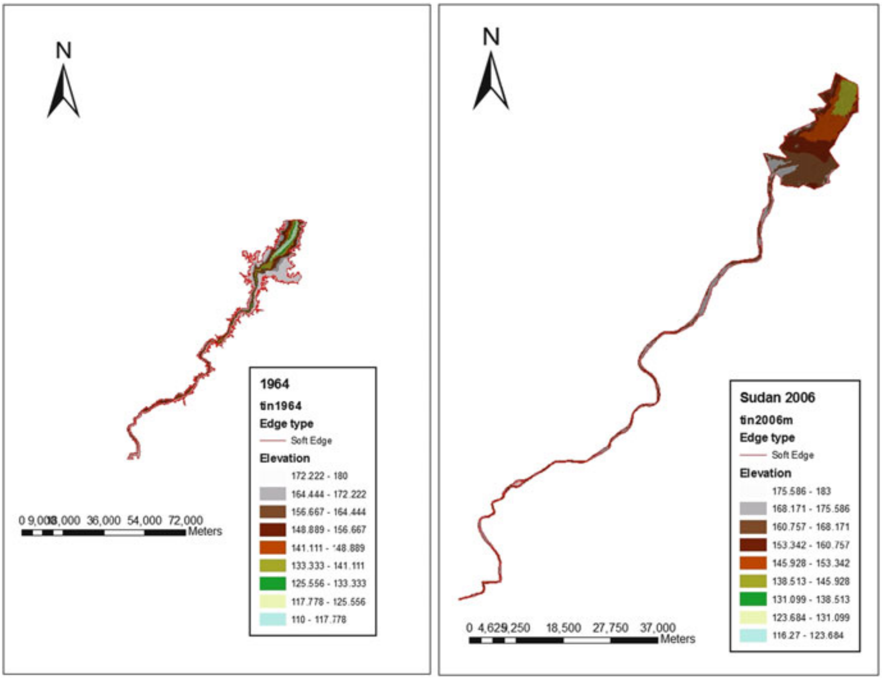

Fig. 8 The interpolated TINs for 1964 and 2006

GIS is obtaining 3-D bathymetry. This is achieved from the collected data of the bed level as scatter points that were interpolated to produce contour lines representing the bed and banks. Three sets were from the Nile Research Institute (NRI). These sets were contour lines and spot level for 1964, 2006, and 2008.

The contour lines of Nile bed level and banks were extracted from data files. They were used to generate scatter points. These will form an irregular triangular net (TIN) by interpolation technique, Fig. 8.

Interpolation technique of scattering points is inverse distance weighted (IDW) method. It is based on interpolating surface that is influenced by nearby points and distant points. The interpolated surface is a weighted average of scatter points and assigned to each point, which diminishes, as the distance from the scatter point increases, Venkatesh [18].

The TIN should be converted to raster files to otain digital terrain model (DTM) representing bathymetry. All DTM files have the same cell size (10 m × 10 m). This type was used in statistical analysis calculations.

7.1.2 Spatial Analysis

The two raster files were used in the logical and mathematical procedure (i.e., algorithm) to calculate deposition volumes. Equation 3 was applied to isolate the topographical surface below the 175 m level which is the water level corresponding to the maximum life span.

$$\text{If } (\mathsf{DTM} \text{ is less or equal than } 175) = \text{logical } \mathsf{DTM} \text{ less than or equal } 175 \tag{3}$$

The logical function on the left-hand side:

If DTM is less or equal 175, it will generate a raster file with the same cells as the original file but with cell values equal to 1 if DTM cell is less than or equal 175 and a cell of 0, if the value is greater than 175.

The logical raster is multiplied by original DTM, such that all values are above 175 m. This will have a zero value, while others will keep original values. The logical and analytical processes were achieved for 2006 and 2008.

To locate the areas where scour and sediment occur, the two bathymetric DTMs of 2006 and 1964 were subtracted from each other and then multiplied by the logical DTM of Eq. 3.

$$\begin{aligned}\text{Morphological raster} = {} & [2006\ \mathsf{DTM} - 1964\ \mathsf{DTM}] \\ & \times [\text{logical } \mathsf{DTM} \text{ less than or equal } 175]\end{aligned} \tag{4}$$

7.1.3 Volumetric Calculations

The resulted raster file, Fig. 9, shows the changes that occurred in the bed during the period from 1964 to 2006 and from 1964 to 2008. Yet, the resulted raster cannot be used to calculate the volume of the scour nor the volume of deposition. However, it can be helpful to locate the locations that were subjected to severe morphological changes.

In order to calculate the volume of bed changes occurred during the period from 1964 to 2006, the following logical and analytical expressions were applied to the resulted morphological changes raster.

$$\begin{aligned}\text{Deposition changes raster} = {} & \text{If (morphological raster greater than 0)} \\ & \times \text{(morphological raster)}\end{aligned} \tag{5}$$

$$\begin{aligned}\text{Scour changes raster} = {} & \text{If (morphological raster less than 0)} \\ & \times \text{(morphological raster)}\end{aligned} \tag{6}$$

The right-hand side of Eq. 5:

If morphological raster is greater than 0, it will generate a raster file with the same number of cells as the original file but with cells equal to 1, whereas depositions occur at a 0, if scour occurs. The logical raster will be multiplied by morphological changes raster. This makes all cell's scour to occur. Deposition occurs and keeps its original value. The logical and analytical procedures are carried to extract deposition and scour, Eqs. 5 and 6.

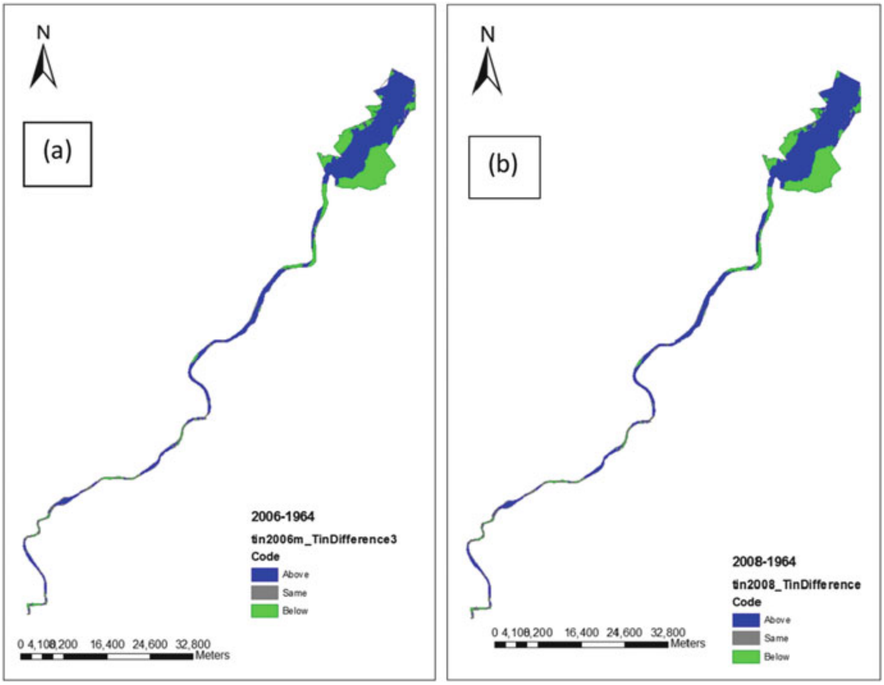

Fig. 9 TINs difference (**a**) 2006 and 1964 and (**b**) 2008 and 1964

The results of Eqs. 5 and 6 are two raster files. One with all the cells, where deposition occurred, is having the deposition depth value, while the rest of the cells have zero values. In addition, the other one shows the scour values for the cells where scour occurred, while the rest of the cells have zero values.

The total volume of scour is calculated by the summation of all cells. Each raster from Eqs. 5 and 6 would be multiplied by 100 m^2 (i.e., area of each cell is 10 m × 10 m), e-cpas.

The same previous steps were repeated for the area for the year 2008.

From Table 2 and Figs. 8 and 9, the total volume at level 175 in 2006 is 4.22 BCM and 4.68 BCM in 2008 for the same level.

7.2 *Traditional Method*

The algorithm is tested against estimated deposition and scour based on the surveyed cross sections to determine the sediment or scour volumes of the river.

The deposited sediment or scour was calculated by assuming distribution to the sediment or scour between cross sections.

The volumes were determined by the area of cross sections and lengths between them. The volume was estimated as the sum of the product of the mean area of two sections and their length e-cpas.

Table 2 The total storage capacity in BCM and surface area km^2 of the AHDR during the period for the year 1964, 2006, and 2008 at different water levels using GIS technique

	1964		2006		2008	
Contour level	Surface area	Volume	Surface area	Volume	Surface area	Volume
110	0	0	0	0	0	0
115	0.07	0	0	0	0	0
120	16.11	0.05	0	0	0	0
125	26.92	0.16	0	0	0	0
130	37.83	0.32	0	0	0.01	0
135	54.61	0.55	0.05	0	0.02	0
140	80.37	0.9	0.21	0	0.1	0
145	108.43	1.38	19.74	0.05	8.72	0.01
150	143.28	2.02	45.08	0.21	34.54	0.12
155	181.24	2.85	74.42	0.5	64.06	0.37
160	214.02	3.84	106.16	0.95	95.11	0.77
165	255.39	5.02	161.12	1.61	138.3	1.34
170	299.77	6.41	239.84	2.6	210.69	2.2
175	368.26	8.11	263.7	3.89	263.12	3.43

In this research, the volumes corresponding to level (175) will be used in the comparison between GIS method and traditional method for 2006 and 2008 in the Sudanese part which contains almost 85% of the total deposited sediment in Aswan High Dam Reservoir.

The total volume at level 175 in 2006 is 4.7 BCM using the traditional method, but GIS method gives 4.22 BCM for the same level.

On the other hand, the total volume at level 175 in 2008 is 5.2 BCM using the traditional method, but GIS method gives 4.68 BCM for the same level.

It can be concluded that the traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing to the traditional method.

8 Percentage of Volume of Sedimentation for Every Cross Section to All Cross Sections of the AHDR

Table 3 represents the volume of sedimentation for every cross section and the percentage of this volume to total volume of sedimentation in AHDR. The maximum percentage of volume is 16.86% in cross section 26 at km 357.0 U.S AHD and the min. Percentage of volume is 2.32% in cross section 19 at km 466.0 U.S AHD. Generally, the average percentage of the most of the cross sections is around 5%.

Table 3 Volume of sedimentation in BCM during the period from 1964 to 2012 and percentage of the volume of sedimentation for every cross section to the total volume of sedimentation of the AHDR

			1964		2012	
Cross section	Km U.S AHD	Repressing length (km)	Volume BCM	Percentage %	Volume BCM	Percentage %
23	487	17	0.121	2.51	0.174	3.08
19	466	19.5	0.15	3.11	0.131	2.32
16	448	17.5	0.204	4.23	0.193	3.41
13	431	16.25	0.287	5.95	0.283	5.01
10	415.5	13.75	0.329	6.82	0.326	5.77
8	403.5	10.75	0.287	5.95	0.269	4.76
6	394	12.5	0.307	6.37	0.298	5.27
3	378.5	11	0.349	7.24	0.353	6.24
D	372	5.25	0.197	4.09	0.197	3.48
28	368	4	0.231	4.79	0.23	4.07
27	364	5.5	0.576	11.95	0.584	10.33
26	357	6	0.725	15.04	0.953	16.86
25	352	5	0.433	8.98	0.785	13.89
24	347	7	0.626	12.98	0.876	15.5
		Sum	4.822		5.653	

9 The Thickness of Sedimentation on the Lowest Point at All Cross Sections During 1964–2012

Table 4 shows the thickness of sedimentation on the lowest point at all cross sections during the period from 1964 to 2012. The maximum thickness of sedimentation on the lowest point is 58.42 m in cross-section D at km 372.0 U.S AHD for the period from the year 1964 (before construction of the AHD) to the year 2012 (the end of the study). These thicknesses varied from 11.04 m in the entrance of AHDR then increasing to the max value 58.42 m in cross-section D at km 372.0 U.S AHD then decreasing the reach around zero in cross-section EL-Madeek at km 130 U.S AHD as shown in Fig. 12.

Figure 10 explains the relation between the storage capacity of the AHDR in billion cubic meters and the years at different water levels from water level 147.0 m (MSL) to water level 180.0 m (MSL) during the period from the year 1964 to the year 2006.

10 Results and Analysis

From Figs. 11 and 12, it is clear that the velocity is decreased in the downstream direction due to the increase of the cross-section area. The d_{50} and TSS also decrease in the downstream direction due to the decrease in the water velocity and their

Table 4 The thickness of sedimentation on the lowest point at all cross sections during period 1964–2012

S. No	C. S. No	Km U.S AHD	Thickness of sedimentation (m)
1	23	487.00	11.04
2	19	466.00	12.42
3	16	448.00	30.82
4	13	431.00	28.06
5	10	415.50	32.66
6	8	403.50	41.86
7	6	394.00	57.5
8	3	378.50	50.6
9	D	372.00	58.42
10	28	368.00	35.42
11	27	364.00	17.02
12	26	357.00	42.32
13	25	352.00	55.2
14	24	347.00	43.7

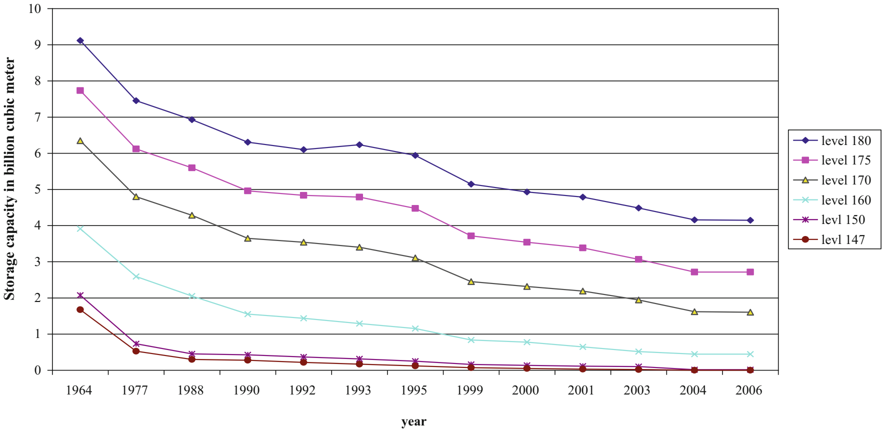

Fig. 10 Storage capacity in M m^{3}of the AHDR at different water levels during the period from the year 1964 to the year 2006

capability to carry up the sediment particles. These explain that almost 82% of the sediment deposit in the first 150 km from 500 km length (the total length of the lake). In addition, almost 18% of the sediment deposit in the last part of the lake 350 km inside the Egyptian border.

Table 5 represents the total storage capacity of the AHDR in Sudanese borders at the year 1964 at different water levels: underwater, level 147.0 m, between the water level 147.0 and 175.0 m, and between water level 175.0 and 180.0 m. It also represents the total storage capacity of the AHDR and sedimentation at the year

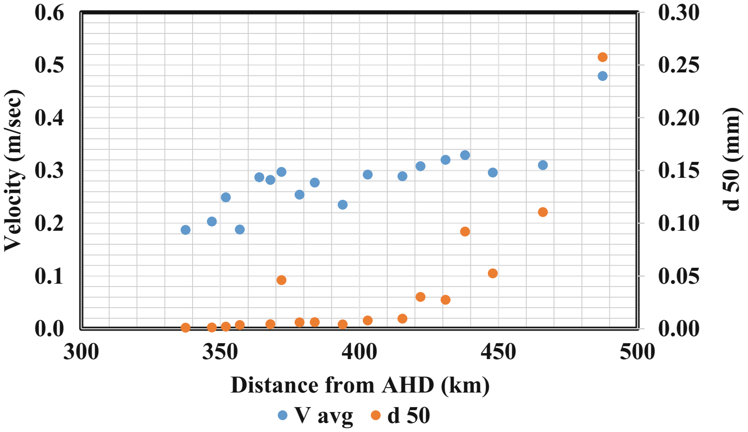

Fig. 11 The relationship between velocity and d_{50} in the Sudanese part in 2006

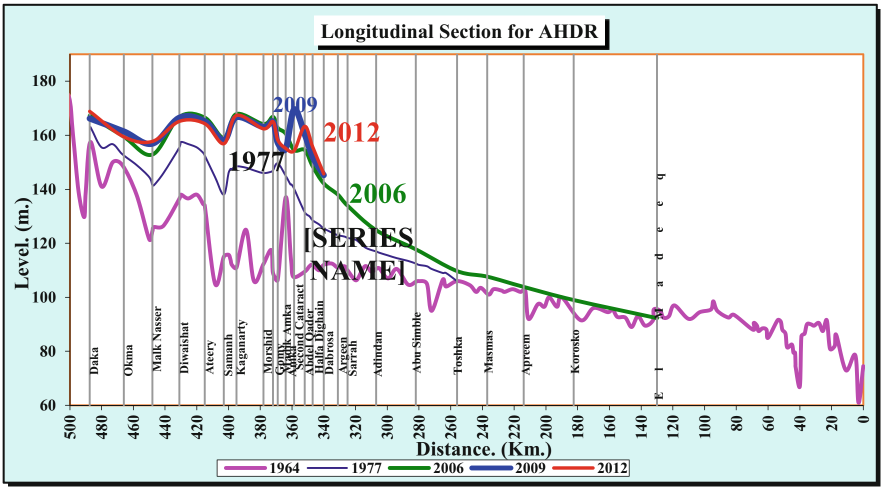

Fig. 12 Longitudinal section of the lowest bed elevation of AHDR from the year 1964 to 2012

2006 at different water levels, at water level 147.0 m, between the water level 147.0 and 175.0 m, and between water level 175.0 and 180.0 m, and the percentage of sedimentation and percentage of the storage capacity of the AHDR at the year 2006 at different water levels. At water level 147.0 m, the storage capacity at the year 1964 equal to 1.673 BCM reduced to zero at the year 2006. At water level between 147.00 and 175.00 m, the storage capacity at the year 1964 equal to 6.06 BCM reduced to 2.715 BCM in the year 2006, and the sedimentation equals to 3.345 BCM. At water level between 175.0 and 180.0 m, the storage capacity at year 1964 equals to 1.380 BCM and still the same value in year 2006 without any sedimentation in this level. At water level under 180.0 m, the storage capacity at the year 1964

Table 5 The volume of sedimentation and storage capacity in B.C.M in Sudanese borders of the HADR at different water levels until 2012

WL	Total storage at 1964	Sedimentation at 2012	Storage at 2012	% Sediment at 2012	% Storage at 2012
<147	1.673	1.673	0	100	0
147–175	6.060	3.862	2.198	63.73	36.27
175–180	1.380	0	1.38	0	100
Sum	9.113	5.535	3.578	60.74	39.26

equal to 9.113 BCM reduced to 4.095 BCM in the year 2006, and the sedimentation equals to 5.018 BCM. The percentages of sedimentation at the year 2006 are 100.0% at water level 147.0 m, 55.20% at water level 147.0 m to 175.0 m, 00.0% at water level 175.0 m to 180.0 m, and 55.06% at water level under 180.0 m.

11 Conclusion

- The total volume at level 175 in 2006 is 4.7 BCM using the traditional method, but GIS method gives 4.22 BCM for the same level.
- On the other hand, the total volume at level 175 in 2008 is 5.2 BCM using the traditional method, but GIS method gives 4.68 BCM for the same level.
- It can be concluded that the traditional method gives overestimate in the calculation of deposit sediment by almost 10% in comparing to the traditional method.
- The total sediment deposit in the Sudanese border until 2012 is 5.535 BCM.
- The total sediment deposit in the Egyptian border until 2012 is 1.2 BCM.
- The total sediment deposit in the AHDR until 2012 is 6.735 BCM.
- The percentage of losses from the total reservoir capacity until 2012 (162 BCM at level 182 m) is almost 4.135%.

12 Recommendations

The following are also recommendations for future researches:

- Better data should be collected; especially for velocity distribution, wind speed, and bed load.
- It is clear that changes in the watershed and stream management upstream will have a profound impact on the discharge and the sediment load entering AHDR. Watershed models, which link the sediment production and delivery in the upstream catchments to the sediment transport and deposition in the river channels and reservoirs, will allow us to predict the future behavior of AHDR.

- Future upstream engineering projects should be studied for its effects on the amount of water discharge and sediment deposition in the AHDR.
- Using the different technique to estimate the amount of sedimentation such as GIS and remote sensing.

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Evaluation of Merowe Dam's Effect on the Accumulated Sediment in Lake Nubia, Sudan Using RS/GIS

Mohamed Elsahabi and Abdelazim Negm

Contents

Abstract Constructing dams upstream Lake Nubia (Sudan) may dramatically alter the distribution of its accumulated sediment via reducing the annual flow deposition rate into this lake based on their design criteria. This chapter aims to estimate the

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annual inflow sediment rate into Lake Nubia before and after the operation of Merowe Dam. Therefore, the following equal length periods (2000–2003) before its operation and (2009–2012) after its operation are considered to evaluate the effect of the dam construction on the accumulated sediment in Lake Nubia. This will be achieved utilizing remote sensing (RS) and geographic information systems (GIS) techniques by utilizing the 3D profiles of Lake Nubia study area. The results of the present approach based on RS/GIS are compared to obtained results using the complimentary cross sections (the traditional method adopted by Aswan High Dam Authority, AHDA). The results indicate that the annual sedimentation rate was reduced by about 2.57 million cubic meter (2.04%). Also, results indicated that the present approach overestimated the annual sediment rate by about 3.50%, before and after the operation of Merowe Dam compared to the results of the method adopted by AHDA. This low reduction percent indicates that the effect of Merowe Dam on the reduction of the incoming annual sediment rate to Lake Nubia is minor and can be neglected compared to the effect of huge upstream dams such as Grand Ethiopian Renaissance Dam (GERD).

Keywords 3D profile, GIS, Grand Ethiopian Renaissance Dam (GERD), Lake Nubia, Merowe Dam, Remote sensing, Sediment rate

1 Introduction

The Nile River extends for 6,700 km with a total catchment area of nearly 3 million km^2. There are three main tributaries that feed into the Main Nile, and these are the White Nile, the Blue Nile, and the Atbara River (see Fig. 1). “This river crosses an extremely wide band of latitude originating about 4°S and emptying at 32°N” [2]. “There are a number of dams that exist along the Nile” [3] which include Aswan High Dam (AHD), Merowe Dam on main course of the Nile River in Sudan, Khashm el-Girba Dam on Atbara River, Sennar Dam, Roseires Dam, and GERD (under construction) on Blue Nile (see Fig. 1). These dams disrupt the natural flow of the Nile River and trap sediments that would have normally gone to the Mediterranean Nile Delta. These dams create artificial reservoirs. Sedimentation in these created reservoirs is the process of sediment deposition after dam completion and operating. Also, these dams inevitably lead to physical and ecological changes downstream of the reservoirs’ site, as well as in the reservoir itself, and in some cases also upstream [3].

Accordingly, constructing the Merowe Dam upstream AHD, as an example, reduces the incoming sediment rate per year into Lake Nubia dramatically as they trap part of suspended sediment load every year in its created reservoir (Merowe reservoir) and consequently reduces the sediment budget.

The accumulation of reservoir’s sediment is always accompanied by severe problems which affected severely the reservoirs’ functions such as storage loss, delta deposition, energy loss, blocking intakes and outlets, etc. [4]. These problems are common in all countries, whether they are developed or developing countries

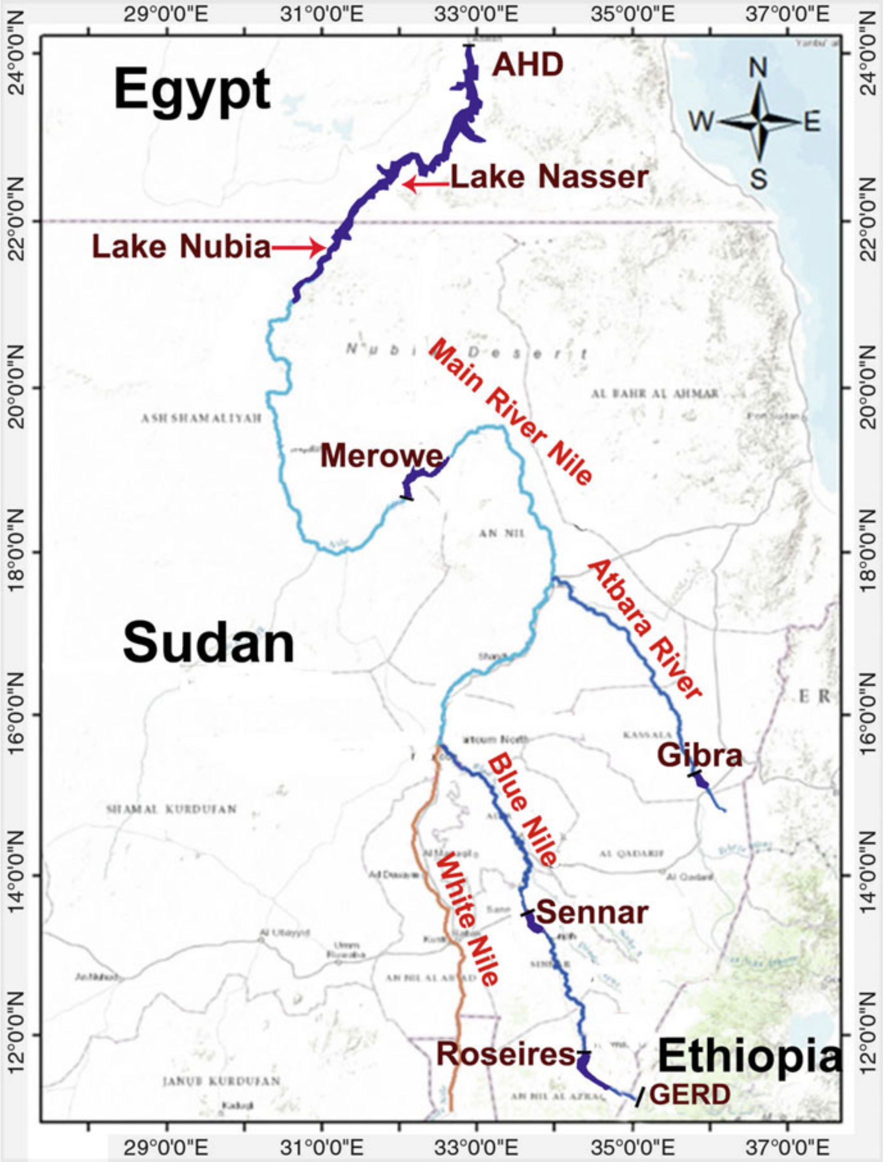

Fig. 1 The location of dams on the main tributaries of the Nile River, after [1]

[3]. Therefore, it is of utmost importance to estimate the annual deposited sediment rate in these reservoirs to help decision makers in these countries to find solutions of these problems and to improve the operating system to meet the design objectives of the reservoir [4].

Some previous studies were concerned with studying the current state of the Nile Basin reservoirs' sediment, for example [4–6]. On the other hand, few previous studies, which were implemented before completely constructing the Merowe Dam, studied the impact of this dam on AHD reservoir, i.e. [7, 8].

To the best of the authors' knowledge, no detailed relevant literature concerning about the impact of Merowe Dam, after its complete construction, on accumulated sediment in AHDL have been published. Recently, RS and GIS techniques are widely utilized to study and estimate lake sediment via analyzing the changes in its bed surface. The capability of combining RS data with in situ measurements, using GIS analyst tools, to estimate and analyze sediment pattern in lakes has been proved in several studies [9–14].

Therefore, the purpose of this chapter is to evaluate the contribution of Merowe Dam to the accumulated sediment in Lake Nubia, Sudan. In this context, comprehensive analysis of the total amount and the annual rate of deposited sediment in the active sedimentation portion within Lake Nubia before and after Merowe Dam construction is done using RS and GIS techniques.

2 Study Area

2.1 Merowe Dam in Brief

The construction of Merowe Dam began in 2004 and finished in March 2009 [3]. It is located on the Nile River at 18°40′08″N and 32°03′01″E, about 800 km downstream of the capital of Sudan (Khartoum) [15] and about 1,000 km upstream the entrance of AHDL [1]. The dam is 67 m high with 1,250 MW hydropower generation capacity. Merowe reservoir storage capacity is 12.4 billion m^3 [5, 7]. Figure 2a shows the location of Merowe Dam and AHDL (Lake Nasser and Lake Nubia) on an acquired image on 15 March 2018 from Landsat satellite (Google Maps). For more details about Merowe Dam and its reservoir, interested readers can consult references [7, 16, 17].

2.2 Active Sedimentation Portion (Study Area)

The present study focuses on the northern portion of the Sudanese part of AHDL (Lake Nubia) which extends between latitudes 21°44′30″N and 22°00′00″N (upstream AHD as shown in Fig. 2b). This portion is called the active sedimentation portion, as it represents the area with most intensive sediment deposition. NRI [18] highlighted that about 50–70% of the total amount of sediment in AHDL were deposited in this portion of the lake, although this portion represents only about 6% of the total area of AHDL [19]. For more details about AHDL and Lake Nubia, references [11, 13] can be consulted.

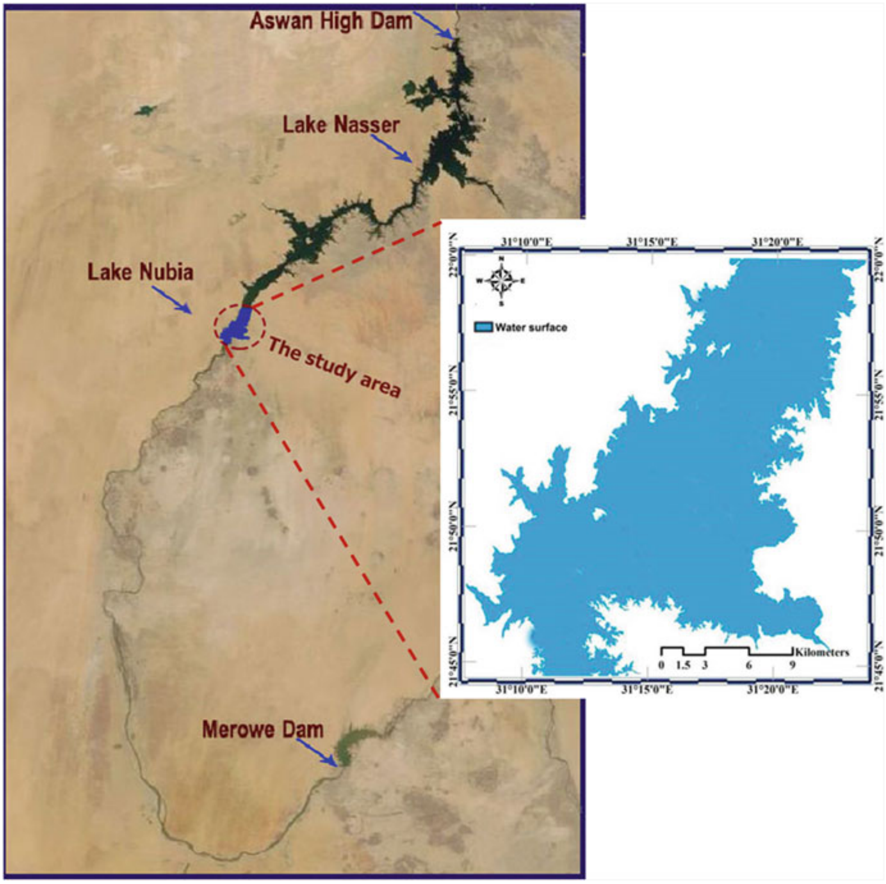

Fig. 2 Location of the Merowe Dam, Aswan High Dam, and Aswan High Dam Lake (Lake Nasser and Lake Nubia) on a Landsat satellite image acquired image on 15 March 2018, with zooming out of the study. Source: Google Maps, 2018: https://www.google.com.eg/maps/@23.3572384,30.6999484,1836855m/data=!3m1!1e3

3 Collected Data

3.1 Hydrographic Survey Data

The hydrographic survey data were conducted in the format of easting, northing, and elevation (E, N, and Z) coordinates by both AHDA and Nile Research Institute (NRI) [18] using the echo sounder device. These data were used to describe the geometry of the active sedimentation portion for the years 2000, 2003, 2009, and 2012.

3.2 Remote Sensing (RS) Data

Three Landsat ETM + images, with (path/row = 175/045), are used in the current study to extract surface boundaries of the study area. Table 1 indicates the acquired dates of the Landsat images of a 30 m spatial resolution for the study area and the study area water levels corresponding to these dates. The satellite images were downloaded freely from the earth explorer USGS website [20].

3.3 Water Level Data

The daily recorded water levels by AHDA gauge stations [21] were collected for detecting levels of the study area of the water surface at the dates of acquiring the Landsat images that are indicated in Table 1.

4 Methodology

The tasks which are involved in the flowchart shown in Fig. 3 were performed to achieve the objective of the present study.

4.1 Building 3D Profiles

In this study, the lake 3D profiles, for the years 2000, 2003, 2009, and 2012, are obtained based on the hydrographic survey data and the extracted water surfaces from the satellite images. For more details about the generation of the 3D lake profiles, interested readers can consult Negm et al. [6] and Elsahabi and Negm [13].

4.2 Creation of Maps of Changes

The maps of changes which represent the sedimentation and erosion zones were generated to quantify the amounts of accumulated sediment in the study area through the period from the year 2000 to the year 2003 before Merowe Dam construction and

Table 1 The acquired dates of the three Landsat ETM + images and the corresponding water levels

Acquired date	Water level (m)
March 2009	176
March 2006	173
September 2000	178

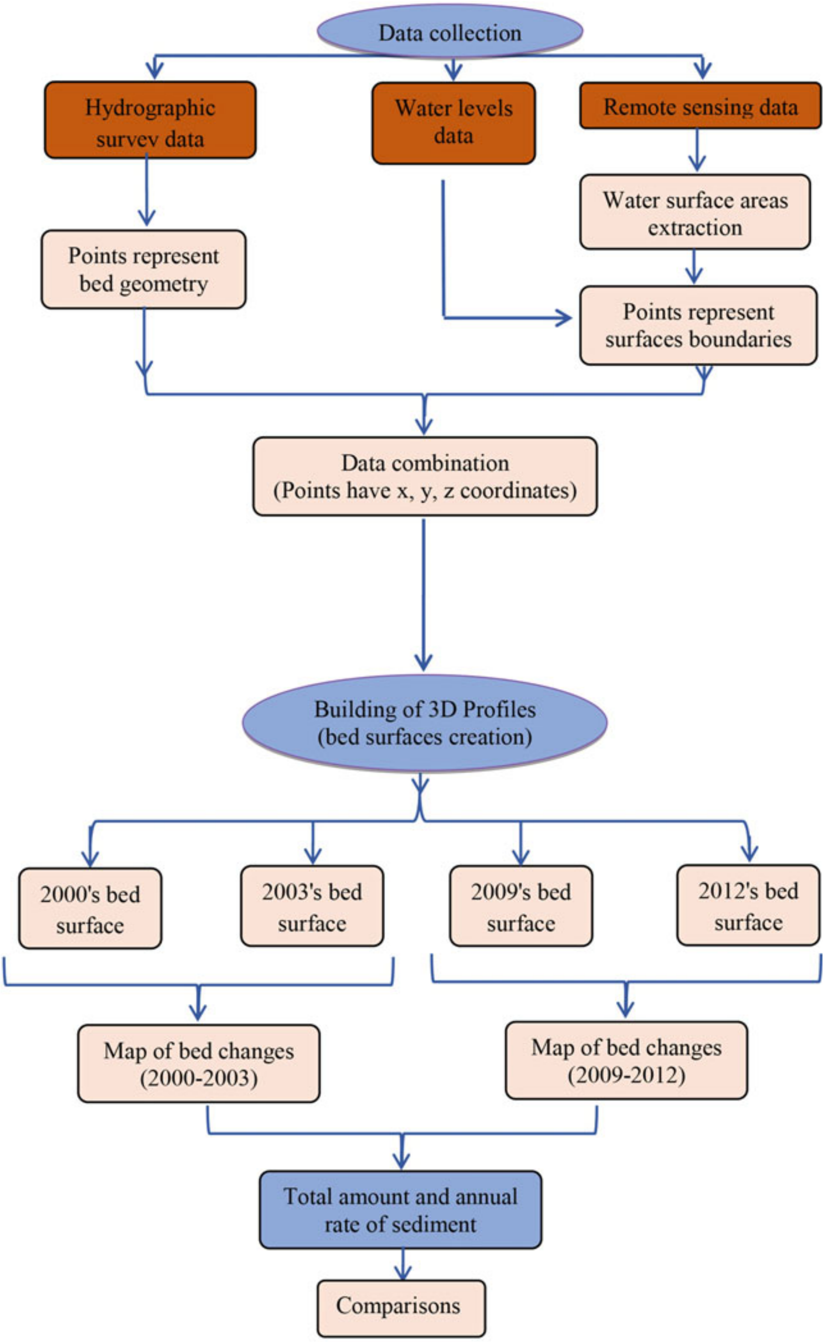

Fig. 3 Flowchart showing methodology adopted in this study to achieve its objective

from the year 2009 to the year 2012 after Merowe Dam construction. The interested reader can consult Elsahabi and Negm [13] and Negm and Elsahabi [22] where full details about the change detection process and creation of maps of changes can be found.

5 Results and Discussions

5.1 Created 3D Profiles

The 3D bed profiles are created for the years 2000, 2003, 2009, and 2012. The results are presented in Figs. 4, 5, 6, and 7, respectively. These profiles were used to generate the maps of changes before and after Merowe Dam construction.

5.2 Creation of Maps of Changes

The map of changes for the periods 2000–2003 and 2009–2012 was produced using ArcGIS software [23] and presented in Figs. 8 and 9, respectively. These maps were used to quantify the total amount and annual rate of sediment in the study area.

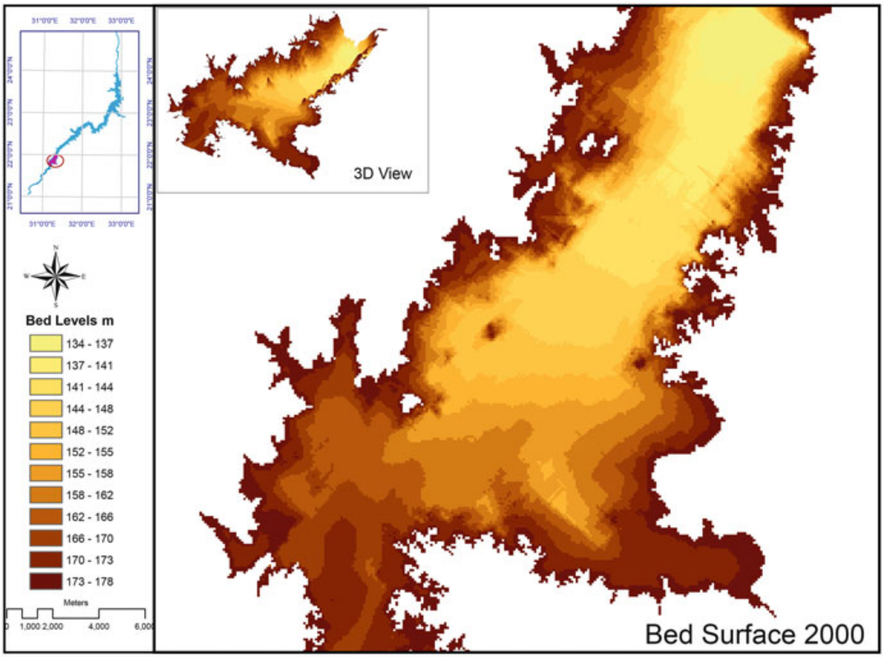

Fig. 4 The created bed profile of the study area for the year 2000

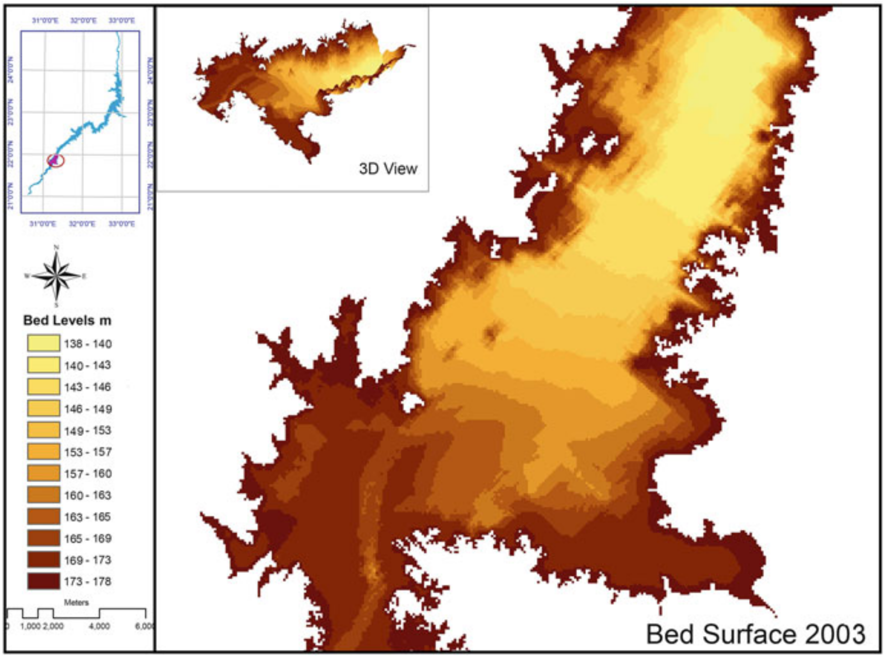

Fig. 5 The created bed profile of the study area for the year 2003

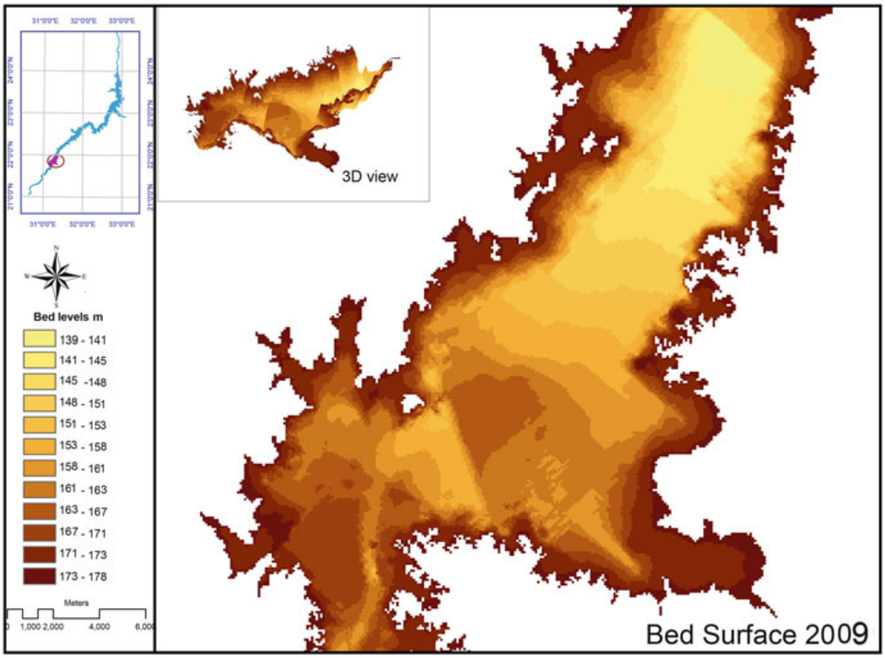

Fig. 6 The created bed profile of the study area for the year 2009

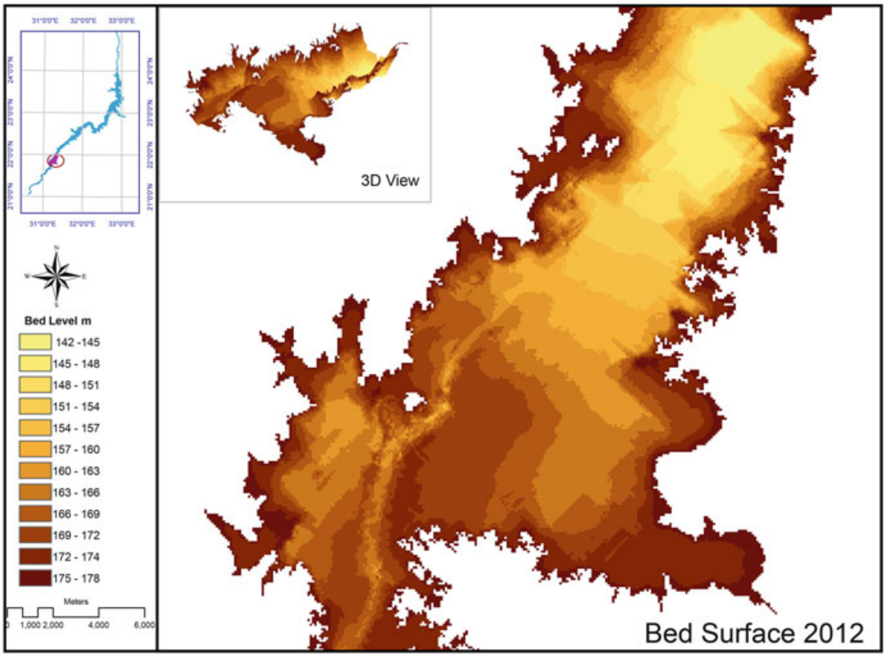

Fig. 7 The created bed profile of the study area for the year 2012

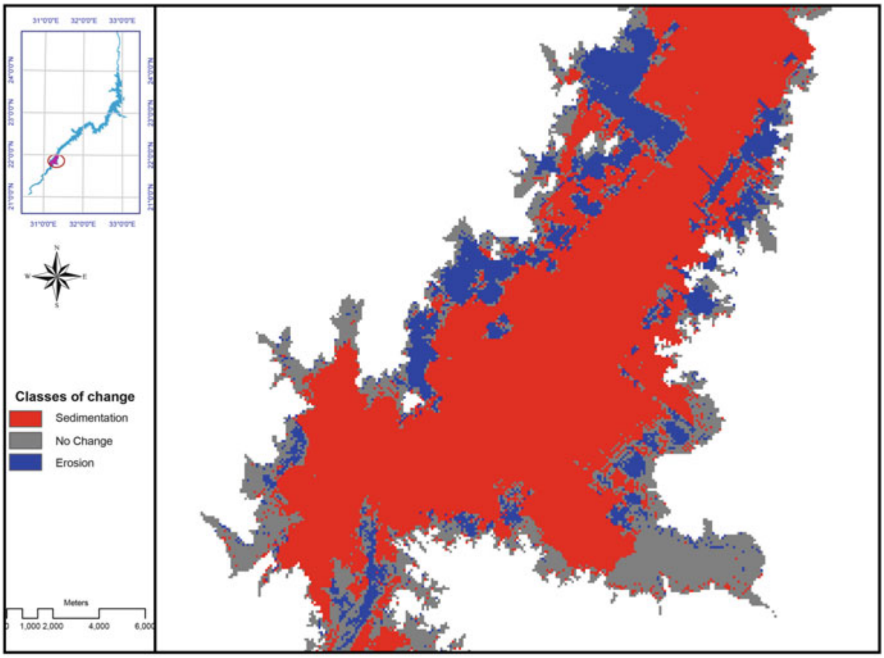

Fig. 8 The created map of changes for the study area for the period 2000–2003

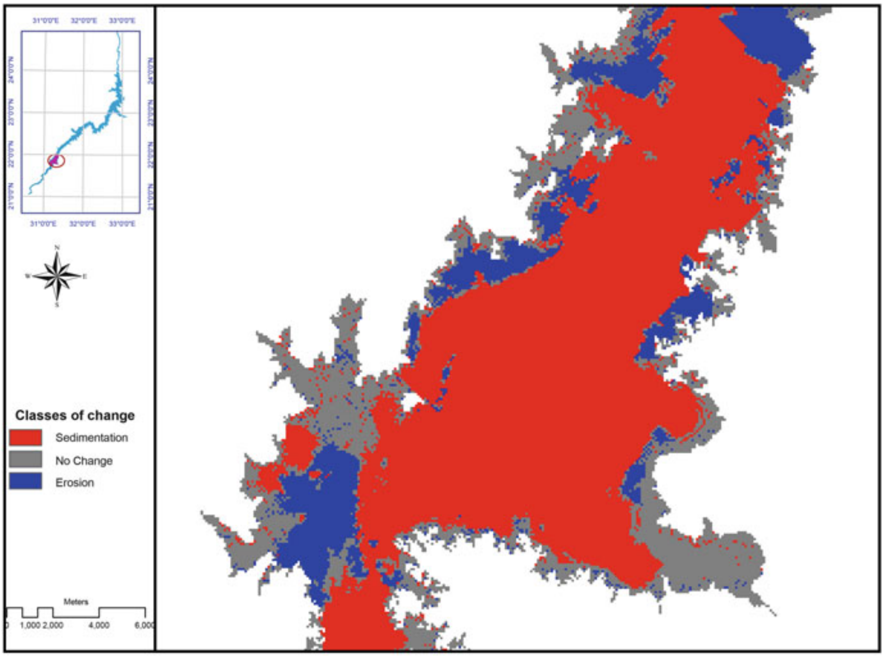

Fig. 9 The created map of changes for the study area for the period 2009–2012

5.3 Estimating Total Amount and Annual Rate of Sediment

The total sediment amount in the study area of Lake Nubia is computed from the created map of changes shown in Fig. 4. This computation is performed using the statistics of the classes of changes in the created maps of changes [23]. The computed sediment amounts in the periods 2000–2003 and 2009–2012 are given in Table 2 which also shows the annual sedimentation rates within these two studied periods. Furthermore, Table 2 illustrates the sediment amounts and the annual sedimentation rates in the study area within the same studied periods (4 years) before and after Merowe Dam construction according to the cross section (traditional) method. The computed amounts of sediment in the study area are summarized in Table 3. It is evident that the annual sedimentation rate was reduced by about 2.57 million cubic meter (from 126.21 to 123.64 million cubic meter before and after Merowe Dam construction, respectively) using the RS/GIS approach. Also, results indicated that the present approach overestimated the annual sediment rate by about 1.48% and 1.44%, before and after dam construction, respectively, compared to the results of the traditional method adopted by AHDA [18].

Table 2 The computed sediment amounts and rates in the study area within the two studied periods from 2000 to 2003 and from 2009 to 2012

Time period	Method	Total amount of sediment (million m^3)	Annual sedimentation rate (million m^3/year)
2000–2003	The RS/GIS approach	378.63	126.21
	The traditional method [18]	373.12	124.37
2009–2012	The RS/GIS approach	370.92	123.64
	The traditional method [18]	365.67	121.89

Table 3 The reduction in the estimated annual rate of sedimentation due to Merowe Dam construction by both the RS/GIS approach and the traditional method

Reduction using the RS/GIS approach		Reduction using the traditional method [18]	
Amount (million m^3)	Percentage (%)	Amount (million m^3)	Percentage (%)
2.57	2.04	2.48	1.99

5.4 Comparisons

Table 3 indicates the reduction in the estimated annual rate of sedimentation in Lake Nubia study area due to Merowe Dam construction by both the RS/GIS approach and the traditional method which is computed by subtracting the estimated annual rate of sedimentation between before and after Merowe Dam construction.

The obtained results in Table 3 indicated that the present approach overestimated the reduction percentage in the annual sediment rate in the study area due to the construction of Merowe Dam by about 3.5%, compared to the results of the traditional method adopted by AHDA [18].

5.5 Effect of Other Sudanese Eastern Dams

The Sudanese Eastern dams, which were built upstream Lake Nubia, include Khashm el-Girba Dam, Sennar Dam, and Roseires Dam as shown previously in Fig. 1.

5.5.1 Khashm el-Gibra Dam

Khashm el-Girba Dam had been constructed in 1964 on Atbara River to store water for irrigation purposes of New Halfa Scheme (Sudan) [3, 24].

5.5.2 Sennar Dam

The Sennar Dam was completed in 1925 on the Blue Nile to serve the Sudanese needs by providing the basis for agriculture economy in Sudan [3, 4].

5.5.3 Roseires Dam

The Roseires Dam was completed in 1966 to produce hydropower and to store the Blue Nile water that flows into Sudan [3, 4].

Since the three dams (Khashm el-Girba Dam, Sennar Dam, and Roseires Dam) were constructed and entered the service before the construction of AHD [25], their impacts on the accumulated sediment are already include. Therefore, in the opinion of the authors, no need to further investigate their impacts separately on the accumulated sediment.

6 Conclusions and Recommendations

This chapter presents and analyzes the impact of Merowe Dam on the accumulated sediment in Lake Nubia, Sudan. The results indicate that after constructing Merowe Dam in Sudan, the rate of deposition in Lake Nubia study area was decreased by about 2.04% every year. Moreover, this decrease will be about 0.72% after GERD construction. Also, results indicate that the present approach overestimates the annual sediment rate by about 1.50%, before and after Merowe Dam construction, compared to the results obtained by AHDA. According to the results in this chapter regarding the impact of Merowe Dame on the sediment accumulation in Lake Nubia, one can safely conclude that impact of Merowe Dam could be neglected compared to impact of GERD on the same (i.e. the accumulation of sediment in Lake Nubia). The authors are highly recommending to neglect the impacts of the Merowe Dam and all other dams which were constructed before the year 1971.

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Impacts of GERD on the Accumulated Sediment in Lake Nubia Using Machine Learning and GIS Techniques

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Abstract This chapter aims to study and discuss the effect (hypothesis) of constructing the GERD on the deposited sediment amount in the AHDL. To achieve the objective of this chapter; a machine learning approach represented in a regression tree (RTs) model was used and calibrated to simulate the changes in bed levels and water velocities in the study area within AHDL by using the field measured data and GIS analysis for the year 2008 (reference case). Furthermore, a model verification process has been done to ensure the applicability of the applied model using the available field data in the year 2012. The results of the bed levels and velocities during calibration and verification of the model show low values of RMSE % (for calibration 2.90 and 2.57 for bed levels and velocities, respectively, and for calibration 4.66 and 4.98% for bed levels and velocities, respectively) and high R^2 (for calibration 0.9975 and 0.9978 for bed levels and velocities, respectively, and for verification 0.9921 and 0.9959 for bed levels and velocities, respectively), indicating that the model was efficiently calibrated and verified. It shows good agreement between the simulated and measured data (by comparisons of simulated longitudinal and cross sections with the measured ones). Thus, this model is considered trustful and reliable to the prediction of sediment and erosion (bed changes) in the study area within AHDL after GERD construction. Accordingly, four of the possible scenarios are performed through the well-calibrated and verified model by reducing the flow quantity and its associated annual sediment rate by 5–10 and 60–65%, respectively. These scenarios are considered as prediction cases after GERD construction. The impact of GERD construction is then studied by comparing some sections along and across the studied lake portion before and after GERD construction (applied scenarios). This impact appeared clearly as a reduction in the amount of the accumulated sediment (decrease in bed levels) accompanied by an increase in erosion amount. Based on the applied scenarios, results showed that the amount of sediment was reduced by 25–27%, 52–55%, 76–81%, and 90–97% in the year 2030, 2040, 2050, and 2060, respectively, compared to the predicted amount of sediment in the year 2020 without GERD operation/construction. As a positive impact of the GERD construction, the lifetime of the upstream AHD reservoir will be prolonged due to the decrease in the amount of the accumulated sediment. This study provides decision-makers with a preliminary knowledge about the impact of GERD operation/construction on AHDL sediment pattern and consequently on Egypt and Sudan. Moreover, the current study opens new windows for future research to investigate the impacts of the different aspects of GERD of AHDL.

Keywords AHDL, Egypt, Ethiopia, GERD, GIS, Machine learning, Modeling, Regression tree, Sediment

Abbreviations

2D	Two dimensional
3D	Three dimensional
AHD	Aswan High Dam
AHDA	Aswan High Dam Authority
AHDL	Aswan High Dam Lake
$B.m^3$	Billion cubic meters
GERD	Grand Ethiopian Renaissance Dam
GERDP	Grand Ethiopian Renaissance Dam project
GIS	Geographic information systems
NRI	Nile Research Institute
R^2	Determination coefficient
RBF	Radial basis functions
RMSE	Root mean square error
RS	Remote sensing
RT	Regression tree

1 Introduction

Constructing any dams has positive and negative environmental impacts. Some of these impacts extend to affect other countries sharing the same river basins including these dams. This is clear particularly in the case of international rivers. The Nile River is an excellent example of such cases where the construction of the Grand Ethiopian Renaissance Dam (GERD) near to Sudan border was decided without any respect for the international rules.

Constructing the GERD has many effects on the downstream countries specifically Egypt and Sudan. Impacts, for instance, include decreasing the Egyptian Nile water share, decreasing water level at Aswan High Dam Lake (AHDL) at the Aswan High Dam (AHD), decreasing the generated hydroelectric power, decreasing and removing most of the accumulated sediment amount in AHDL, etc.

Many researchers are interested in discussing the GERD's benefits and its impacts on the downstream Nile basin countries [1–13]. Meanwhile, some other studies were concerned with the impact of Grand Ethiopian Renaissance Dam on the High Aswan Dam Reservoir (e.g., [14–16]).

Currently, the amount of sediment in AHDL accumulated upstream (US) of AHD is about 7 billion cubic meter [17]. Before the construction of GERD, the accumulated sediment in AHDL was increasing progressively. This manner will differ entirely after the construction of the GERD. As an effect of the dam construction, a vast amount of sediment will be retained upstream (US) side of the GERD, and the released amount of sediment to the downstream (DS) side will be smaller or neglectable. Assuming that the dam will be completed according to the announced height and storage capacity and assuming that the dam will be used only for power generation, the released water to the DS will be mostly clear water with little fine sediment content. In turn, this hungry water will change the sediment pattern within AHDL.

A part of this sediment will move from the Sudanese part of AHDL (Lake Nubia) to the Egypt side (Lake Nasser) and then may pass (through the AHD to the valley north of Aswan) from the US to DS of AHD. This will cause a realizable reduction in the amount of deposited sediment in AHDL.

Estimation of sediment capacity is one of the essential issues in lakes and reservoirs engineering. Moreover, modeling and predicting the amount of sediment (sediment capacity) in lakes and reservoirs is critical by the side of planning and handling the water resource projects [18]. Also, modeling has become a frequently used tool for studies in hydraulic and environmental engineering [19]. One of the best methods for estimating the sediment capacity in lakes is the creation of 3D bed surfaces of the lakes using RS/GIS techniques [20]. Recently, application of the artificial intelligence (AI) and machine learning have been presented in water resource engineering field. They have been used for the estimation and prediction of different phenomena (such as sedimentation process: sediment amounts, sediment rates, sediment transport, suspended sediment load and concentrations, etc. in lake and river engineering). Machine learning is defined as “programming computers to optimize a performance criterion using example data or experience.” As a discipline, it falls between computing and statistics and is also referred to as statistical learning [21]. The common two methods based on artificial intelligence (AI) and machine learning, which are considered as statistical learning techniques for estimating and predicting sediment amounts and rates, are the artificial neural network (ANN) and decision trees (DT) that include regression trees (RTs) and model trees (MTs). The ANN method was applied in many previous studies for estimating the sediment rates, amounts, and concentrations in rivers and lakes [18, 22–37]. The decision tree (DT) method is another common tool in predicting sedimentation phenomenon [18, 22, 38–42].

In contrast to ANN, DT produces the roles. This means that prediction through DT is based on the role set, while this process in ANN is not translucent and it is like a black box [40].

Besides studying the sedimentation process, there are many other applications of regression trees (RTs) and model trees (MTs) in the water resource engineering field (i.e., [43–47]). In general, any model is a physical or description of a physical system, including the interaction with its outside world, which can be used to simulate the effect of changes in the system itself and the effect of changes in the conditions imposed upon it [19]. There are two types of practical models for studying any environmental phenomena including physical and numerical models. Physical model in the laboratory is done primarily in a large flume or in a river basin model. Moreover, physical modeling results may be used directly by the laboratory's clients in the design of a particular structure, or it may be used to develop predictive numerical models with potential for general application in designing structures [19]. Numerical (computational) analysis is widely used to solve mathematical expressions that describe the physical phenomena. Numerical models are classified by a number of spatial dimensions over which variables are permitted to change. They provide much more detailed results than other methods. They need field data for verification. Numerical models have been extensively and successfully applied to studies on sediment yield, river sedimentation, and morphological processes since the 1970s. The accuracy and reliability of a mathematical model in predicting sediment processes depend to a large extent on understanding sediment transport mechanism of effectiveness of numerical solution methods, calibration and verification by field and experimental data, as well as the user's experience and art. There is, apparently, plenty of room for improvement in these aspects [19].

Referring to AHDL, sediment accumulation in this lake is considered a big issue in the last four decades which threaten the life of this lake and the efficiency of the AHD. Therefore, many studies were concerned with studying and modeling sediment process in AHDL to detect the amount of the accumulated sediment or the mechanism of deposition process (e.g., [48–59]). This chapter presents and discusses the estimation and the prediction of the sediment amount in AHDL after GERD construction by applying a machine learning model (RTs). Different scenarios (cases) can be examined (tested or applied) using the RT model simulations with different flow conditions and values of annual sediment rate ranging from maximum to the minimum possible situation to estimate the predicted amount of sediment in AHDL. To achieve this goal; four of these possible scenarios will be discussed in the present study. From the viewpoint of the authors, the current chapter is considered the first study concerned with detecting the impact of GERD construction on the accumulated sediment amount in AHDL, which is considered the main objective of this study.

2 Description of the Study Area

The study area, which is chosen to be studied under the effect of GERD construction, is a portion of AHDL. This area is involved in the Nile River Basin, particularly in the Sudanese part of the AHDL (Lake Nubia).

2.1 Nile River Basin

The Nile Basin catchment area is about 3.18 million km^2 located in the eastern side of Africa, including the 11 nation-states of Burundi, Democratic Republic of the Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda [8] as shown in Fig. 1. The total population of these countries is about 280 million [9].

The Nile is considered as the longest river in the world (measured over 6,695 km). The Nile has two main tributaries. The Blue Nile originates in the Ethiopian highlands, while the White Nile originates in the Equatorial Lakes region of East Africa in either Burundi or Rwanda. The tributaries join in Khartoum, Sudan, before flowing through northern Sudan and Egypt to the Nile Delta [61]. The total length of the river and its tributaries is about 37,205 km [9]. Concerning the effect of the Blue Nile on the Main Nile; it contributes approximately 57% of the total runoff into the Main Nile as measured inflow to Egypt. On the other hand, the White Nile and the Atbara River supply the largest proportions of water (57% and 14%, respectively) to the Main Nile. Furthermore, the Blue Nile contributes approximately 75% of the incoming annual sediment rate into the Main Nile toward the AHDL [9]. Wheeler et al. [8] stated that "although the majority of precipitation falls in Ethiopia and the Equatorial Lakes region, Egypt and Sudan consume the vast majority of water." In fact, this is not true because Ethiopia is consuming most of the precipitation while Egypt and Sudan consume only most of the surface runoff that reaches the Nile River which is only less than 6% of the total precipitation falling on the basin.

2.2 Aswan High Dam Lake (AHDL)

The AHDL is considered one of the greatest man-made reservoirs in the world, created after the construction of the Aswan High Dam (AHD). The total length of this reservoir is about 500 km along the Nile River including two main parts: the Egyptian part (known as Lake Nasser, 350 km) and the Sudanese part (called Lake Nubia, 150 km). This lake covers an area of about 6,000 km^2 with a maximum width of about 12 km as shown in Fig. 2. Furthermore, the total storage capacity of the AHDL is about 162 billion m^3. The dead storage capacity is 31.6 B.m^3 between levels 85 m and 147 m, and the live storage capacity is 90.7 B.m^3 between levels 147 and 175 m. Moreover, the flood control storage capacity is 39.7 B.m^3 between levels 175 and 182 m.

Lake Nubia, the Sudanese part of the AHDL, is located between latitudes 21° 02′ 00″ and 22° 00′ 00″ N (upstream the AHD) as shown in Fig. 2.

Lake Nasser, the Egyptian part of the AHDL, is located between latitudes 22° 00′ 00″ N (upstream the AHD) and the Aswan High Dam (AHD) in the north as presented in Fig. 2.

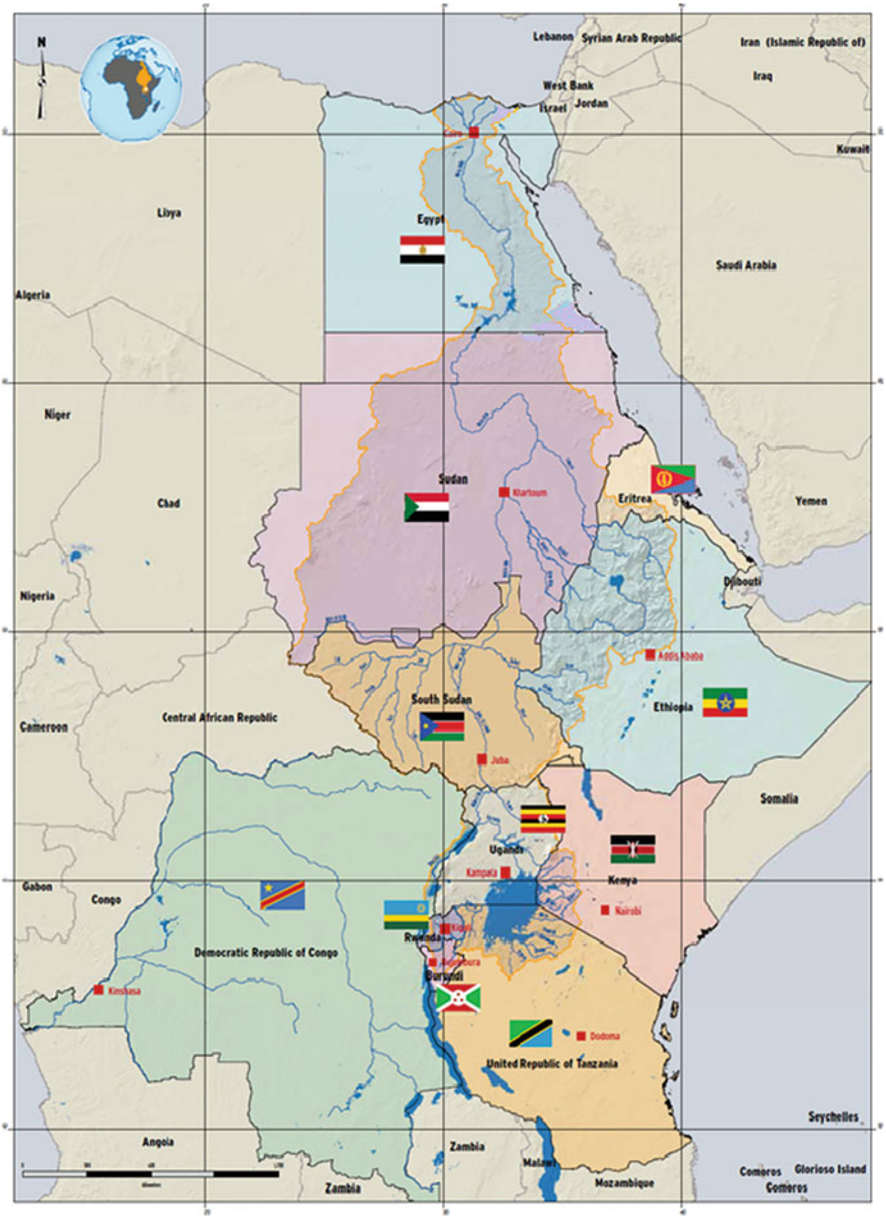

Fig. 1 The Nile River Basin counties map [60]

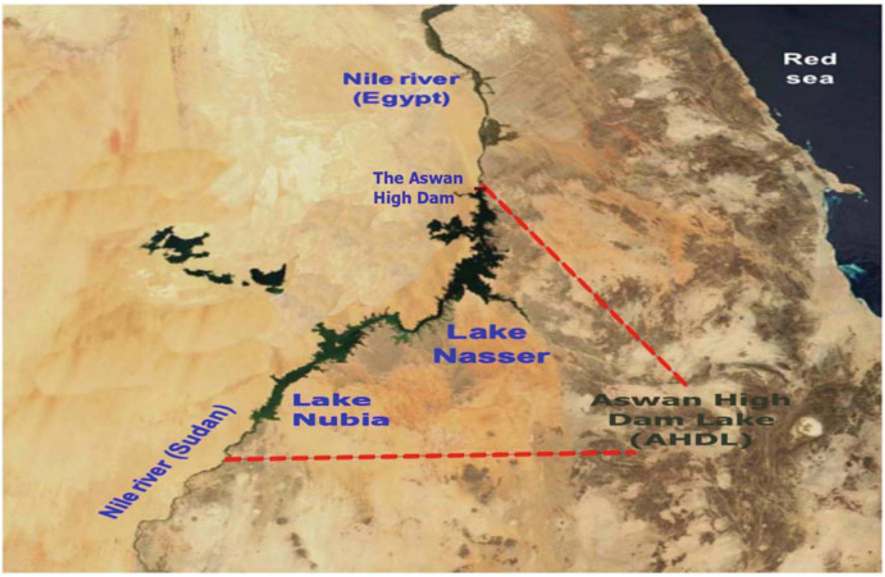

Fig. 2 The Aswan High Dam Lake (AHDL) (Lake Nubia + Lake Nasser = AHDL)

2.3 Active Sedimentation Portion (Study Area)

The present study focuses on an area that extends between latitudes 21°44′30″N and 22°00′00″N (upstream AHD) in the Sudanese part of AHDL (Lake Nubia). It contains six cross sections (28, 27, 26, 25, 24, and 22) from the South to the North, respectively, as shown in Fig. 3. The portion of AHDL refers to the study called the active sedimentation portion area, as it represents the area with most intensive sediment deposition. According to [17], it was found that about 50–70% of the total amount of sediment in AHDL were deposited in this zone of the lake, although this portion represents only about 6% of the total area of AHDL [62].

2.4 The Grand Ethiopian Renaissance Dam in Brief

The GERD is located in Ethiopia; on the Blue Nile about 20 km away from the Ethiopian-Sudanese border. This dam is anticipated to operate with a height of 145 m above the foundation level, and a crest length is 1,780 m. The dam reservoir will extend over the Blue Nile gorge for 246 km with a surface area of 1,874 km^2. This reservoir has a total capacity of 74 B.m^3 with active storage of 59.22 B.m^3 [63]. For more details about GERD project, interested readers can review [3, 14, 63, 64].

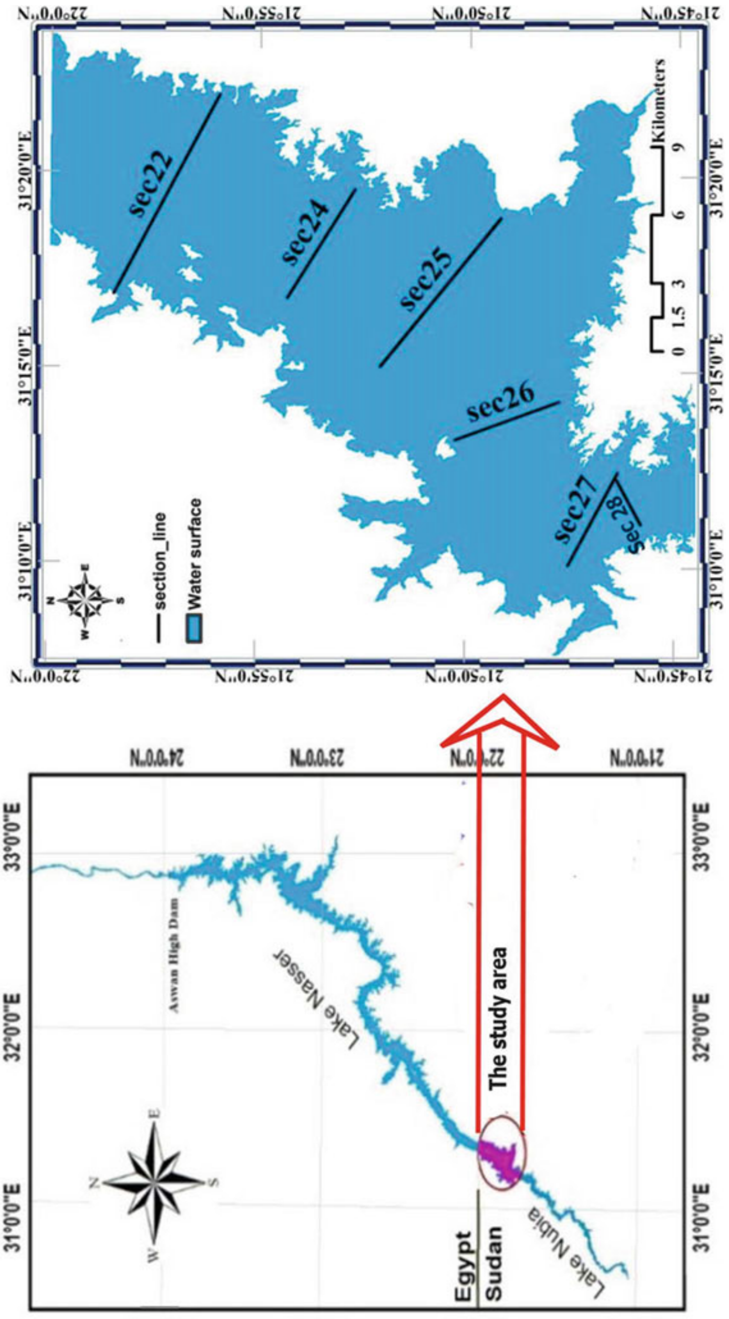

Fig. 3 The study area involved within Aswan High Dam Lake map

3 Collected Data

3.1 Bathymetric (Geometric) Data

These data describe the geometry of AHDR and include the following.

3.1.1 Hydrographic Survey Data

The hydrographic survey data presented by Easting, Northing, and Elevation (E, N, and Z) were used to describe the geometry of the active sedimentation portion for the year 2008. These data were conducted by both AHDA and Nile Research Institute (NRI) using the Odom hydrographic echo-sounder device (Hydrotrac II). It has an accuracy of up to 0.01 m ± 0.1% of the measured depth.

3.1.2 Topographic Maps

Old topographic/contour maps of the Nile River (surveyed in 1944 with a scale of 1:100,000 and in 1949 with a scale of 1:25,000) are considered the source of level points that describe the geometry of the study area within the AHDL at the beginning of the storage process in the lake.

3.2 Sediment Data

3.2.1 Old Longitudinal Section of AHDL

The old field measurements of bed levels taken in 1964 (longitudinal section as shown in Fig. 4) were combined with the 1944–1949 dataset as the points represent the lowest bed for sediment as appoints data to make the bed surface closer to the 1964s surface as much as possible.

3.2.2 Sediment Rate

This rate is represented by the amount of sediment in a million cubic meters that yearly end up in Lake Nasser, the northern part of Aswan High Dam Reservoir, including the deposited sediment in the bed and that passing through the Aswan High Dam to the valley north of Aswan.

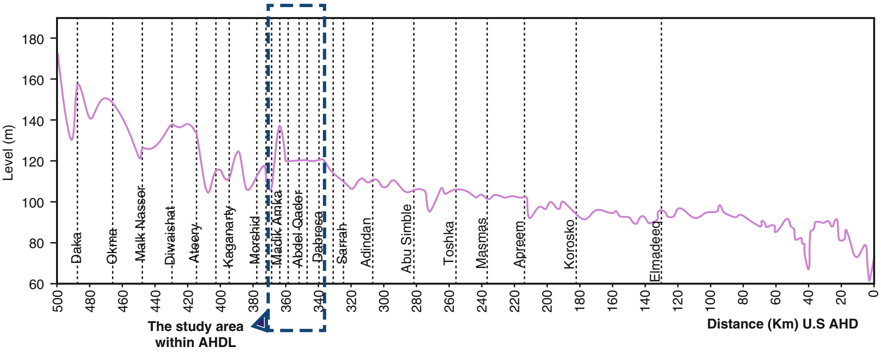

Fig. 4 Longitudinal section in AHDR deepest points in the year 1964 [17]

3.2.3 Lake Bed Material Samples

Collecting the bed material samples from the cross sections (sec22, sec24, sec25, sec26, sec27, and sec28) (see Fig. 3) was carried out using the Grab Sediment Sampler shown in Fig. 5. The samples were collected via the field trips conducted by both AHDA and Nile Research Institute (NRI) and analyzed for grain size distribution in the soil laboratory of AHDA at Aswan City to be dried up. After that, the sieve analysis tests were performed according to the relevant specifications. Finally, the percentage of sediment (bed materials) components, sand, silt, and clay grains (the major components of the collected samples), were determined.

3.3 Remote Sensing (RS) Data

The remote sensing data (three Landsat ETM+ images) are used in this study to extract the study area boundaries. One scene of a Landsat image can entirely cover the active sedimentation portion with path and row values of 175 and 045, respectively. The characteristics of the acquired images for the study area are shown in Table 1. The data were downloaded freely from the earth explorer USGS in level 1 Geotiff (systematic correction) product [65]. These images were geo-referenced by USGS using the world reference system (WGS84 datum) to Universal Transverse Mercator system (UTM) zone, 36 North projections.

3.4 Velocity Measurements

The inflow velocity measurements, which represent the velocity magnitudes, were taken by using a propeller-type Valeport current velocity meter (Braystoke model) device (shown in Fig. 6) via the AHDA and NRI field trips. These data were obtained

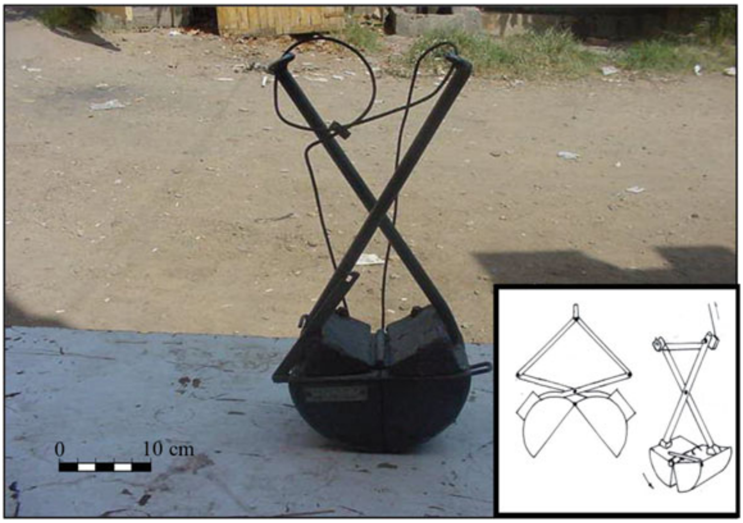

Fig. 5 The Grab Sediment Sampler type

Table 1 The characteristics of Landsat ETM+ images

Satellite	Sensor	Path/row	Date	Spatial resolution	Water level (m)
Landsat 7	ETM+	175/045	September 2000	30 m	178
			March 2006		173
			March 2009		176

at the locations of the cross sections shown in Fig. 3. In this study, the inflow velocity magnitude data for the years 2008 (reference case) and 2012 were used [17].

The velocity was measured at many points along the cross section (at the western third, in the middle, and at the eastern third). At each point, the velocity was measured at three points along the vertical direction, and the average velocity for each point was determined as shown in Fig. 7. It should be mentioned that the flow velocities were measured between the 8th and the 30th of Sep 2008.

For each measurement profile, the average velocity was estimated using Eq. (1):

$$V_{\text{average}} = \frac{V_1 \times 0.2D + \left(\frac{V_1+V_2}{2}\right) \times 0.3D\left(\frac{V_2+V_3}{2}\right) \times 0.3D\left(\frac{V_3}{2}\right) \times 0.2D}{D} \tag{1}$$

3.5 *Hydrological Data*

It is evident that flow discharges and the water levels of any lakes are essential data to simulate the hydrological characteristics of these lakes. For this reason, monthly

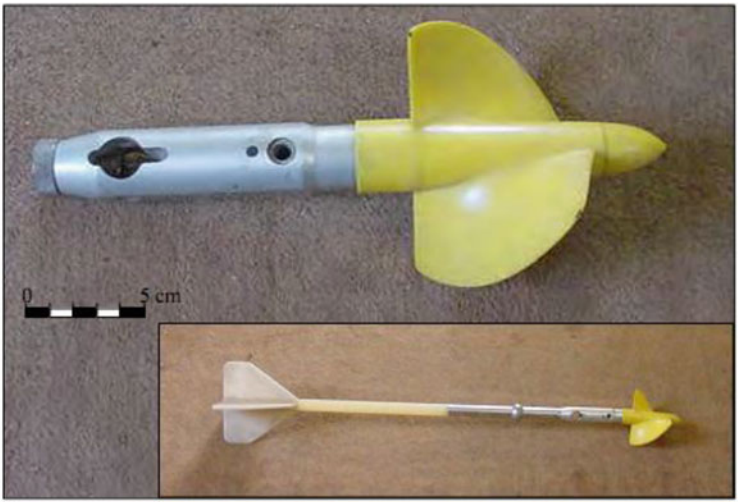

Fig. 6 The used Braystoke-type current meter

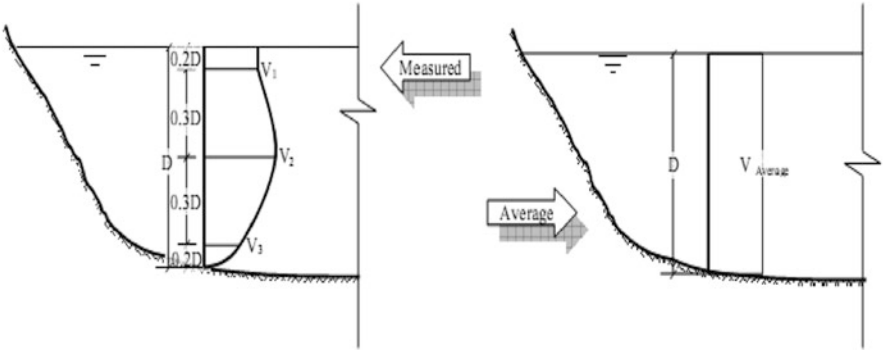

Fig. 7 Determination of the average velocity

monitoring of passing discharges through the AHDL and the daily water levels of this lake as well as at different gauge stations is essential.

3.5.1 Inflow Quantity Data

The total discharge (inflow) which arrived in Aswan (entering Egypt) for the last 20 years were recorded by AHDA according to Dongola gauge station [62].

3.5.2 Water Level Data

Water level upstream AHD were recorded by AHDA gauge stations in the different dates of the year [66]. These data were collected not only for setting up the applied model in this study but also for detecting the water surface levels of the study area at the dates of acquiring the satellite images.

4 Methodology

This section describes the steps used by the authors to achieve the objective of the present chapter. The methodology used to study the research objective is shown in Fig. 8.

4.1 RT Model Setup

In setting up any empirical models, it is necessary to specify their initial boundary conditions and algorithms.

4.1.1 Model Concept

Classification and regression trees are common machine learning techniques to build prediction models based on historical data. These models are generated by (1) recursively partitioning the data and (2) fitting a prediction model for all partitions. The partitioning is typically expressed as a decision tree. This tree is designed for variables that take a number of random values. The regression tree method is one of the predictive modeling methods employed in machine learning and data mining [67]. The regression tree method constructs a model of a dependent variable Y (output variable) as a function of independent variable X (input variable). When the data has many features interacting in complicated, nonlinear ways, creating a single global model can be complex. An alternative way to nonlinear regression is to subdivide the space into smaller regions, in which the interactions between features are easy to be managed. We then partition the subdivisions again (recursive partitioning) until we get to set of the space in which it is easy to fit simple models. Indeed, the generated global model has two parts: the recursive partition and a simple model for each set of the partition. Each of the leaves (nodes) of the tree refers to a cell of the partition, and this cell has a model that spread over in the cell. A point x has its place to a leaf if x falls in the equivalent cell of the partition. To discover what the current cell is, we start with the root node of the tree and query some questions about the features. The inner nodes are labeled with some questions,

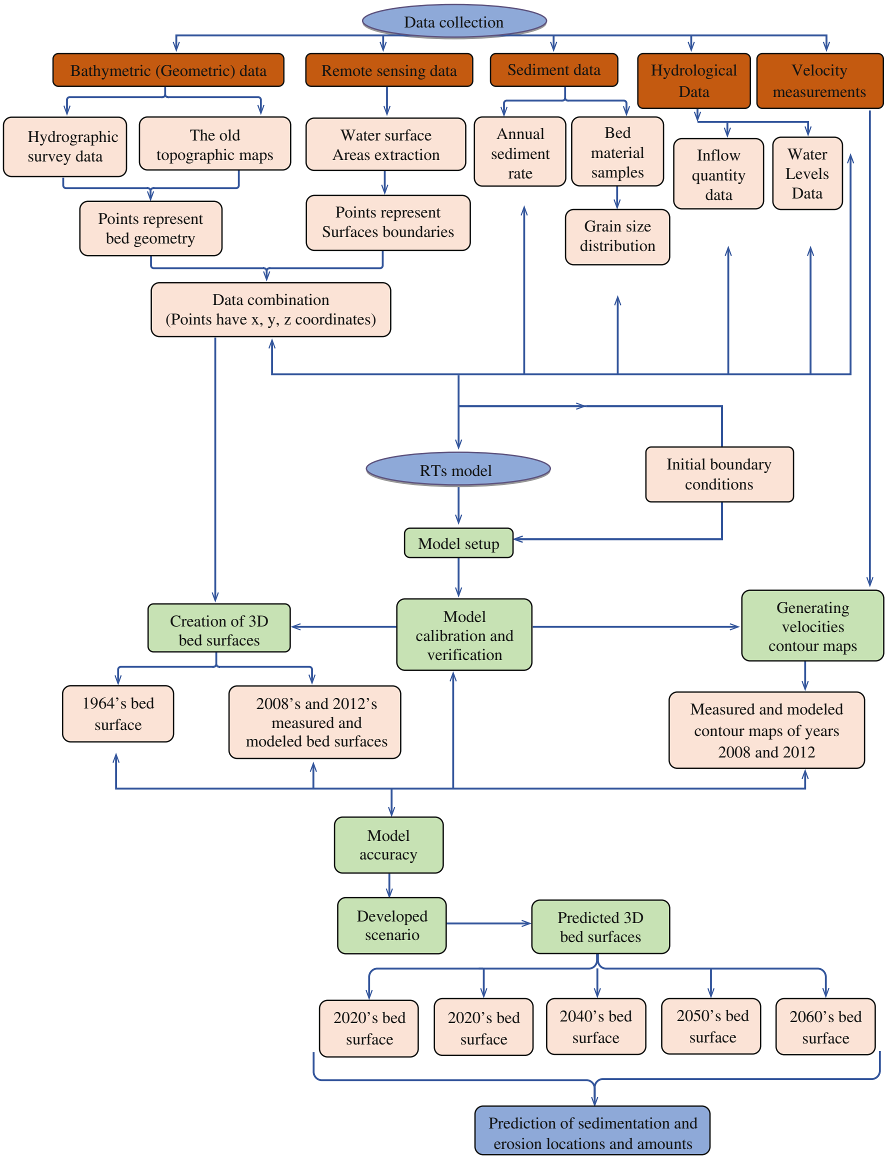

Fig. 8 A flowchart involving the applied methodology steps to achieve the study objective

and the branches between them are labeled by the answers. In the standard version of regression trees, each question denotes only a single attribute and has a yes or no answer, e.g., "Is age > 50?". It is important to notice that the variables do not need to be of the same type. For standard regression trees, the model in each cell is a constant prediction of Y. Assume the points (x_i, y_i), (x_c, y_c) are all the samples for the leaf node l. Then, the model for node l is $\bar{y} = {}^{1}\Big/_{c}\sum_{i=1}^{c} y_i$ (the sample average of the variable).

For example, Fig. 9 shows a tree that represents the interaction between X1 and X2. It is clear from this figure that if X1 $>$ 0.6, X2 no longer matters. When they are equally important, the tree switches between them. The sum of squared errors for a tree T is

$$S = \sum_{c \in \text{leaves}(T)} \sum_{i \in C} (y_i - m_c)^2$$

where $m_c = \frac{1}{n_c} \sum_{i \in C} y_i$ is the prediction of the leaf c. We can rewrite the above equation as follows:

$$S = \sum_{c \in \text{leaves}(T)} n_c V_c$$

where V_c is the leave variance of the leaf c. Therefore, we will make the splits to minimize S.

4.1.2 Model Algorithms

The steps of RTs algorithm, shown in Fig. 10, can be summarized as follows:

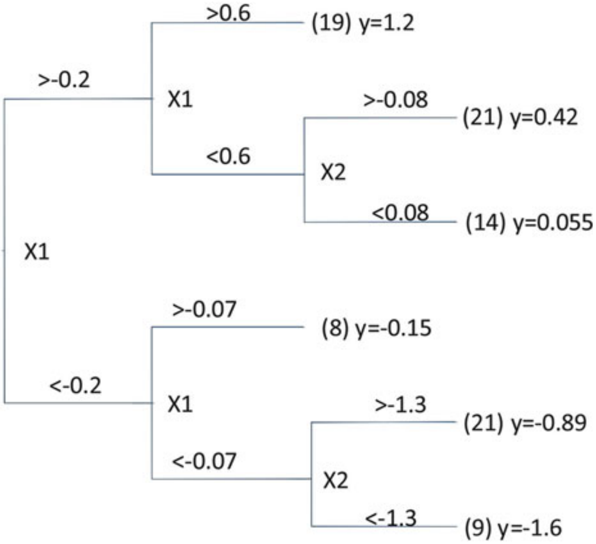

Fig. 9 A simple example for RTs

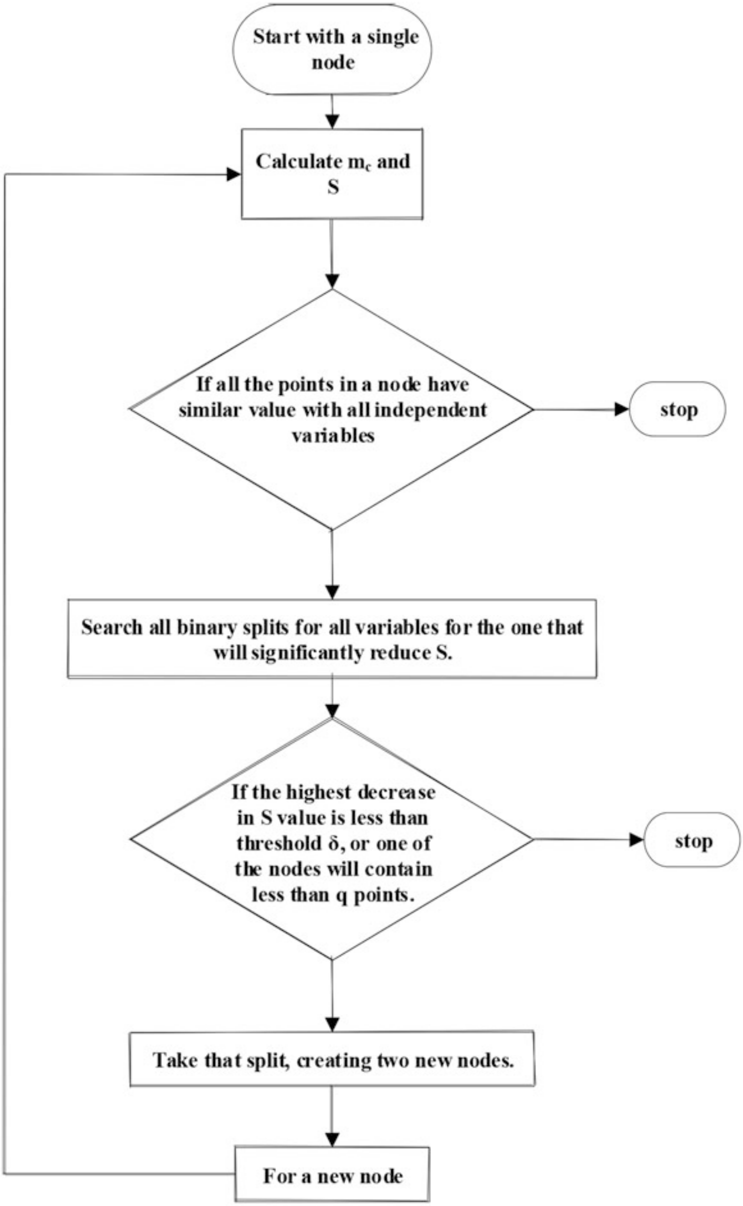

Fig. 10 Flowchart of the RT algorithm

1. The calculation process starts with one node which includes all points.
2. Compute m_c and S.
3. If all points in a node have equal value for all variables, stop the process; else look for all binary splits of all variables for the one that minimizes S. If the highest

decrease in S would be less than some threshold δ, or one of the subsequent nodes would comprise less than q points, stop the process; else, take that split, and then create two new nodes.
4. For a new node, go to step 1.

4.1.3 Boundary and Initial Conditions

The initial conditions represent the data in the year 2008 which are used as inputs (X) for the applied model in this study. These data in brief include lake's bed geometry (x, y) data, bed level values, sediment data (annual sediment rate, grain size distribution), measured average velocities data, and hydrological data (water levels, inflow discharge). The measured bed levels and the average water velocities for the year 2008 and year 2012 are used to calibrate and to verify the model, respectively (in the calibration and verification processes), as they will be the outputs (Y) of the model.

4.2 Model Calibration

Model calibration is a procedure of adjusting the model inputs to match the model outputs with the field observation data for the selected period. The applied RT model is calibrated using the necessary field data (e.g., average velocity distribution and bed levels) in the year 2008 along two cross sections (sec.24 and sec.25), as shown previously in Fig. 3, and a longitudinal section that passes through the deepest points within the study area (the active sedimentation portion).

4.3 Model Verification

The model verification has been conducted to check the model performance. The measured data in the year 2008 are taken as a reference, and the predicted bed levels and the average velocity values in the year 2012 are computed with the necessary changes according to the model inputs (taking into consideration the difference in the period). The model is then verified by comparing the computed average velocities and bed levels in the year 2012 along with the same considered sections in the calibration process.

The purpose of model calibration and verification is to measure the ability of the applied model as a prediction tool for both the velocity distribution and bed level changes along the considered study area. Moreover, it is vital to satisfy both the model calibration and verification before using its computations (bed level changes) as results for the prediction of sediment and erosion locations and amounts in the chosen study area. It is worth to mention that the model has been applied to predict the bed level changes to be used in estimating sediment and erosion capacities along the study area of the lake. This is made for two cases, without GERD in place (at the year 2020) and after GERD's full operation (construction) at years 2030, 2040, 2050, and 2060.

4.4 Creation of the 3D Bed Surfaces

To generate continuous knowledge about the bed levels of the study area, it was necessary to approximate the level values in areas that were not included with measurements (level points). This was done using the radial basis functions (RBF) interpolation method. For more information about the RBF method, interested readers can review the help topics of ArcGIS software [68].

The 3D bed surfaces of the lakes are an essential data source for the assessment of sediment deposition in these lakes. In this study, the lake 3D bed surfaces for the year 1964 and for both years 2008 and 2012 observed and modeled data are obtained using the RBF spatial interpolation function. Then they are used to produce the map of changes. Moreover, the obtained cross sections and the longitudinal section from the observed and modeled bed surface maps in the year 2008 for calibration and in the year 2012 for verification are also used to evaluate the RT model accuracy (the calibration and verification accuracy).

The map of changes, created by overlaying the created bed surfaces using the 3D analyst tool in ArcGIS software [68], represents the changes (sedimentation/erosion) in zones. This map was created to quantify the amounts of sediment and erosion in the study area from the year 1964 to the year 2008 and from the year 1964 to the year 2012.

4.5 Generating the Inflow Velocity Contour Maps

To establish the inflow velocity contour maps for years 2008 and 2012, the available inflow velocity values were used in the interpolation process. This process was performed by using ArcGIS software. These contour maps were produced in order to check the accuracy of the applied model for simulating the velocity magnitudes in the year 2008 and for predicting the velocity magnitudes in the year 2012 via the obtained cross sections and the longitudinal section from these contour maps.

4.6 Model Accuracy

To evaluate the model performance by checking the accuracy of its calibration and verification process results, statistical analysis has been done in the current chapter. Based on the measured average velocities and bed levels in different cross sections (sec.24 and sec.25) and longitudinal section, two statistical parameters were calculated to evaluate the performance of the model (if the model is an accurate tool for predicting the future's bed levels changes or not). The statistical parameters, which were used in the evaluation process, are tabulated in Table 2.

4.7 Scenario Analysis

The developed (calibrated and verified) model is used to simulate the changes in the study area. Also, it is used to identify areas of actual and potential erosion and deposition (via creating the map of changes) resulting from various tested scenarios (cases for a prediction after GERD operation). Four scenarios are developed based on assuming reduction percentage for inflow quantity and annual sediment rate by about 5–10% and 60–65%, respectively. Those assumptions are inspired from results, discussions, and hypotheses of some previous studies about sediment rate and inflow quantity before and after GERD construction [7, 9, 12, 13, 15]. Those assumptions are summarized in simple charts created by the authors, as shown in Fig. 11, based on the previous studies. These charts indicate the contribution percentage of White Nile, Blue Nile, and Atbara in sediment rate and inflow quantity that move toward the AHDL before and after GERD operation.

The expected effect of these scenarios on the morphological changes (sediment/erosion location and amounts) was then detected in the study area.

The four scenarios include:

- Scenario (1): 10% flow reduction associated with 65% sediment rate reduction
- Scenario (2): 10% flow reduction associated with 60% sediment rate reduction
- Scenario (3): 5% flow reduction associated with 65% sediment rate reduction
- Scenario (4): 5% flow reduction associated with 60% sediment rate reduction

Table 2 Statistical indicators for calibration evaluation [69][a]

Parameter	Abbreviation	Amount (B.m^3)
Root mean square error	RMSE	$\sqrt{\sum (\text{Mes} - \text{calc.})^2 / N}$
Determination coefficient	R^2	$\sum(\text{calc.} - \text{avg. Mes})^2 / \sum(\text{Mes} - \text{avg. Mes})^2$
Percent of RMSE	RMSE (%)	(RMSE/avg. Mes) × 100

[a] *Mes* measured value, *calc* calculated value, *avg.* average value

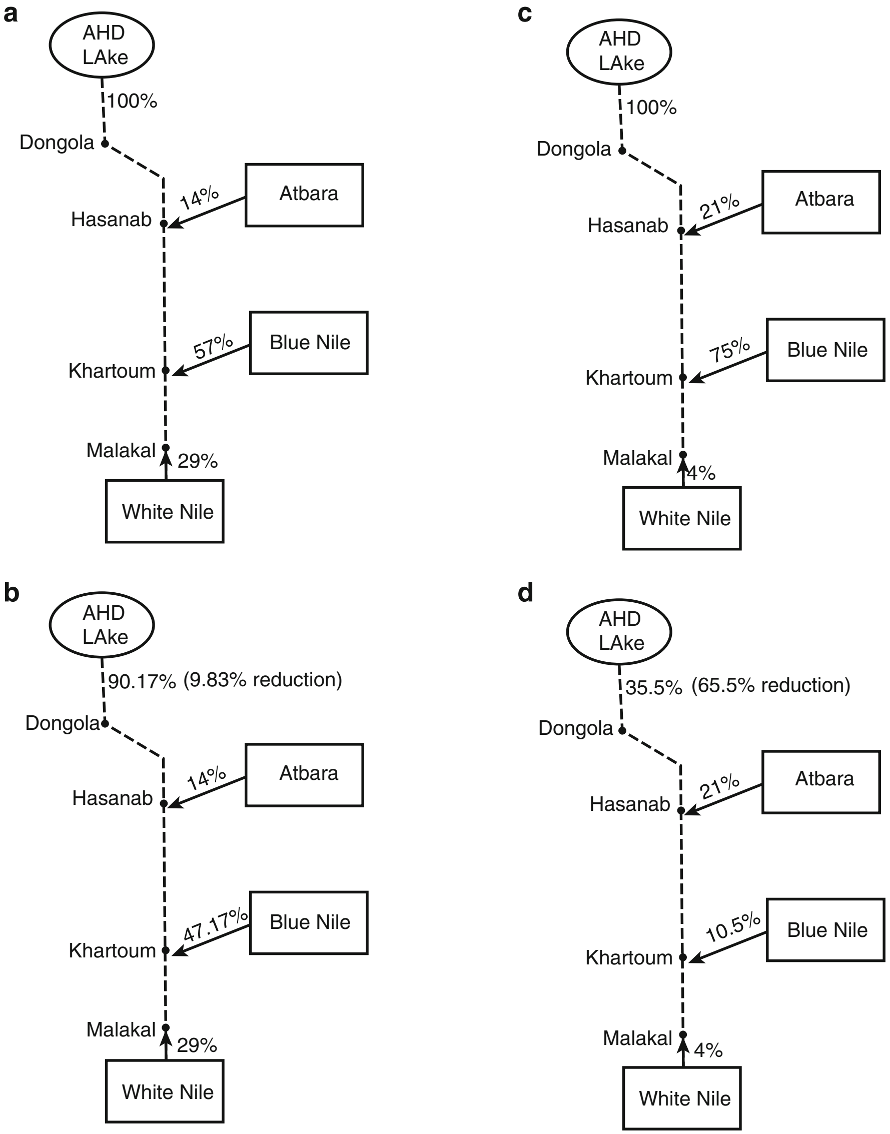

Fig. 11 Schematic of the model scenario assumptions: (**a**) inflow quantity % without GERD [9], (**b**) average inflow quantity % with GERD [7, 9, 12, 13, 15], (**c**) incoming annual sediment rate % without GERD [9], and (**d**) incoming annual sediment rate % with GERD [9]

The results of these scenarios will help the decision-makers and the ones responsible for managing AHDL to make a sustainable development of this lake and to regulate the operation rules of the AHD for the upcoming years after GERD construction.

4.8 Prediction of the 3D Bed Surfaces for the Upcoming Years

The level point data which are derived for the year 2020 (cases without no GERD in place) and from the developed four scenarios (after GERD construction) through the applied RT model are used in the interpolation process for the upcoming predicted years (2020, 2030, 2040, 2050, and 2060) to predict 3D bed surfaces of the study area at those upcoming years. The interpolation process is performed with the radial basis functions (RBF) method [68]. The predicted 3D bed surfaces for the study area were used to produce the map of changes from the year 1964 up to those upcoming years.

4.9 Prediction of Sediment and Erosion After GERD Operation

In this stage, the predicted bed surface maps for the years 2020, 2030, 2040, 2050, and 2060 according to their produced bed level values are overlaid with the bed surface map (before AHD construction) created in 1964 to produce the maps of changes. The maps represent the change categories over the bed of the lake study area (sediment and erosion). According to these maps, the amount of sediment and erosion can be detected for the years 2020, 2030, 2040, 2050, and 2060 using the 3D analyst tool in ArcGIS software [68].

5 Results

5.1 Results of the Base Case (Reference Case)

The results of this case (for calibration process) can be summarized as follows:

The created bed surface maps for the year 2008 from the observed date and from the modeled date are shown in Fig. 12.

The created maps in Fig. 12 are used to check the accuracy of the calibration process. On the other hand, the created bed surface map for the year 1964 before AHD construction is shown in Fig. 13.

The maps of changes between 1964 and observed 2008 and between 1964 and modeled 2008 are shown in Fig. 14.

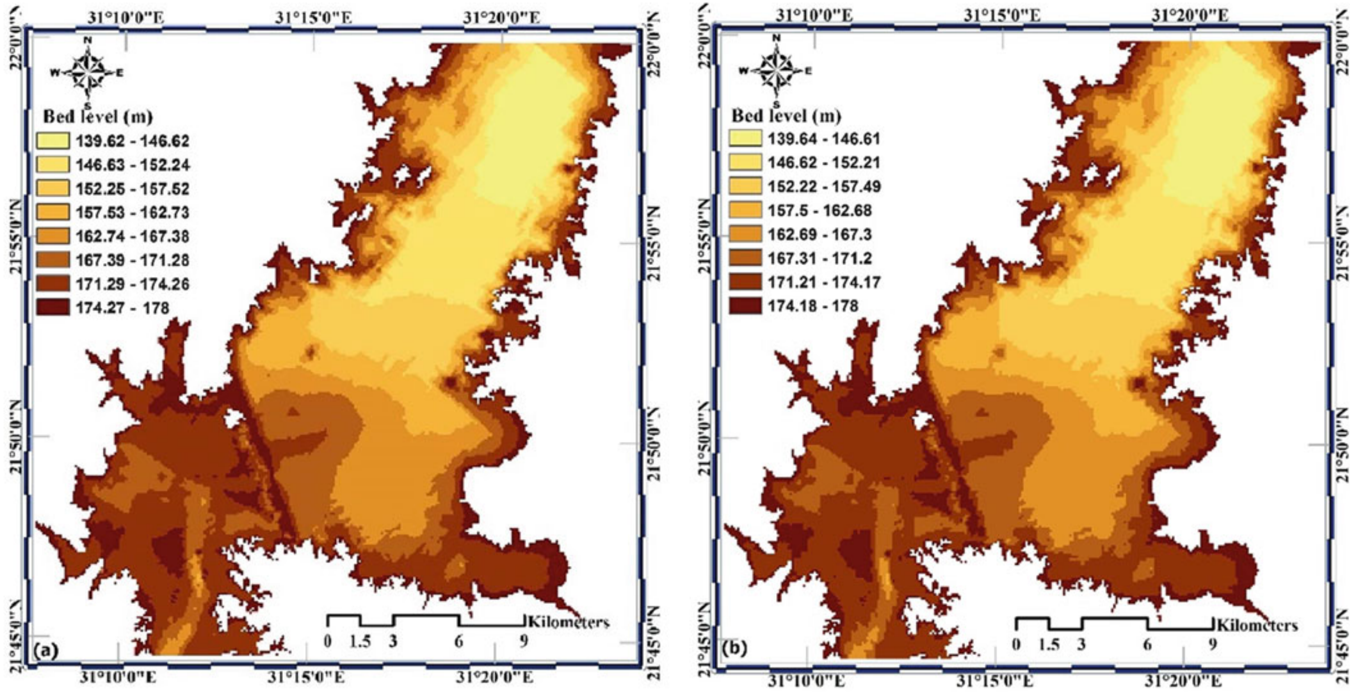

Fig. 12 The created bed surfaces of the study area: (**a**) The observed bed surface map for the year 2008 and (**b**) the modeled (predicted) bed surface map for the year 2008

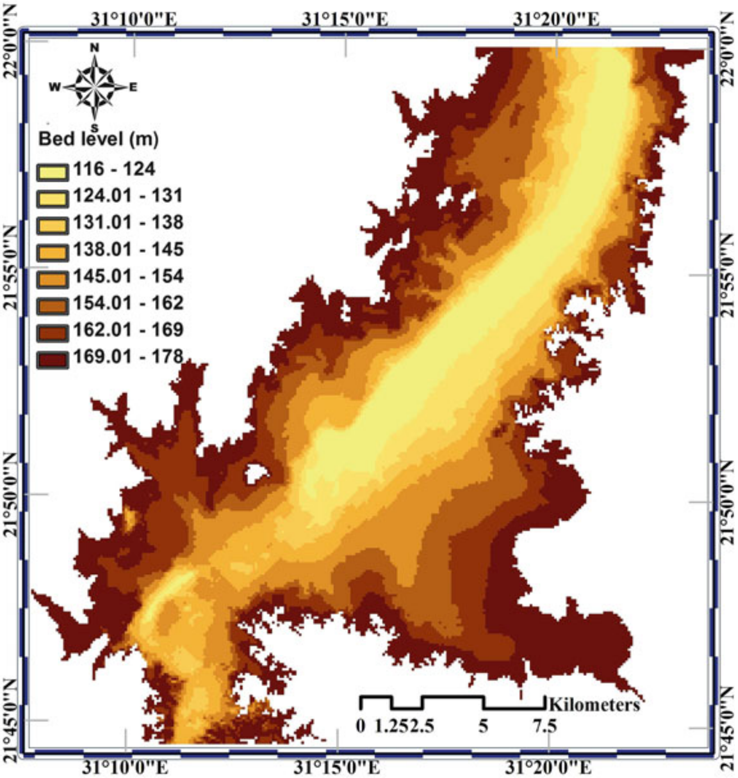

Fig. 13 The created bed surface of the study area for the year1964

The velocity distribution maps for the year 2008 according to the observed data and according to modeled measurements are shown in Fig. 15.

5.2 Results of the Modeled Case for Verification

The results of this case (for verification process) can be summarized as follows:

The created bed surface maps for the year 2012 from the observed date and from the modeled date are shown in Fig. 16.

The created maps in Fig. 16 are used to check the accuracy of the verification process.

The maps of changes between 1964 shown in Fig. 13 and observed in 2012 and between 1964 and modeled in 2012 are shown in Fig. 17.

The velocity distribution maps for the year 2012 according to the observed data and according to modeled measurements are shown in Fig. 18.

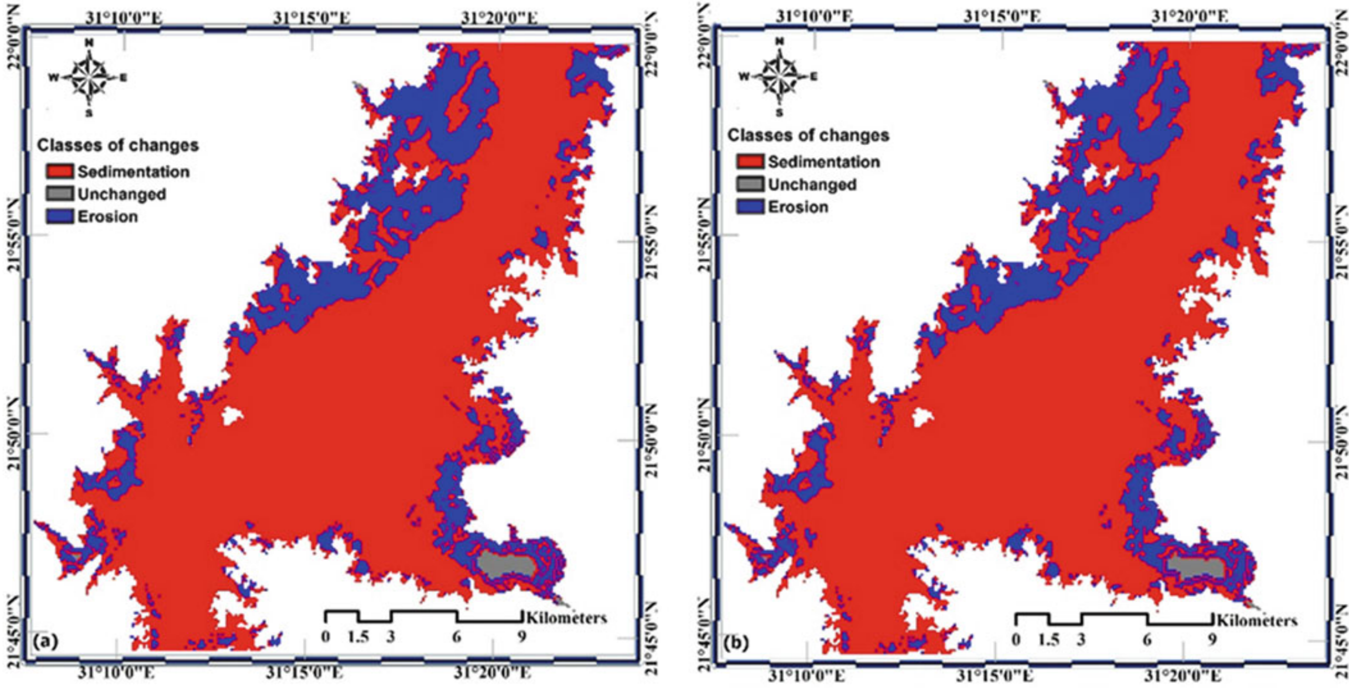

Fig. 14 Map of changes (**a**) observed for the period 1964–2008, (**b**) modeled for the period 1964–2008

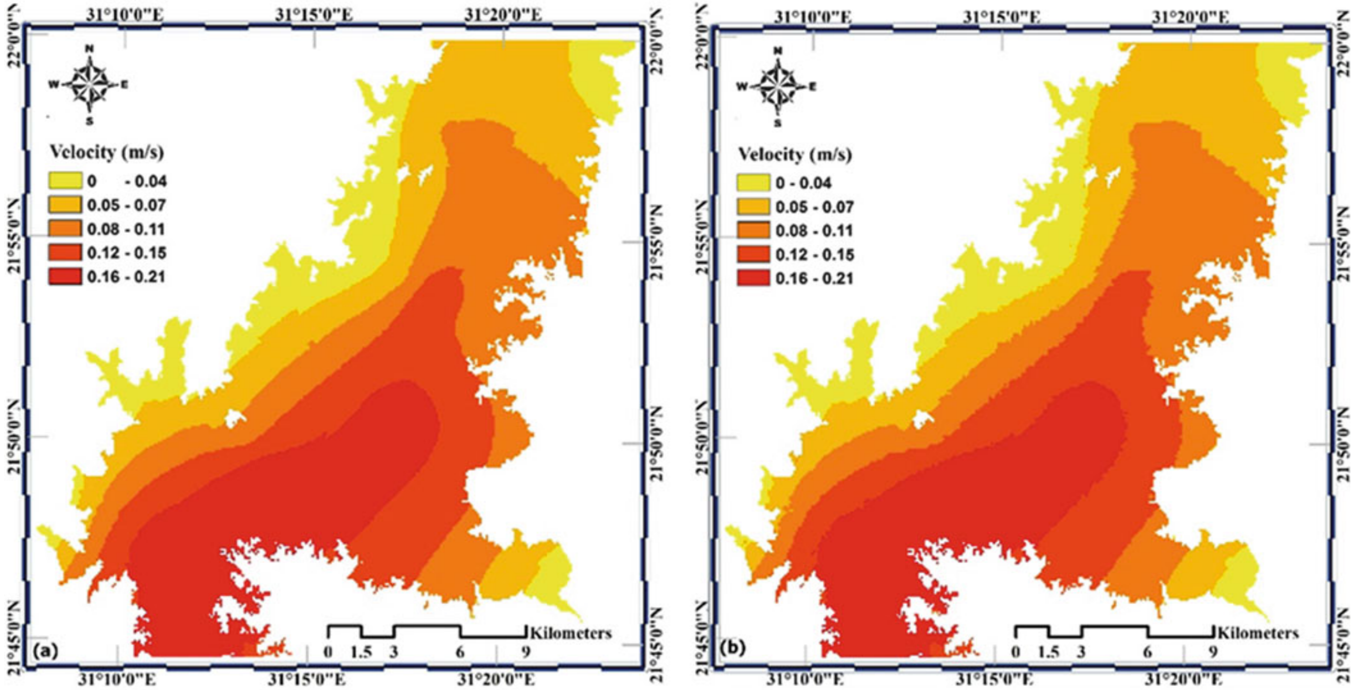

Fig. 15 Velocity distribution map (**a**) for the observed data in 2008 and (**b**) for the modeled velocities in 2008

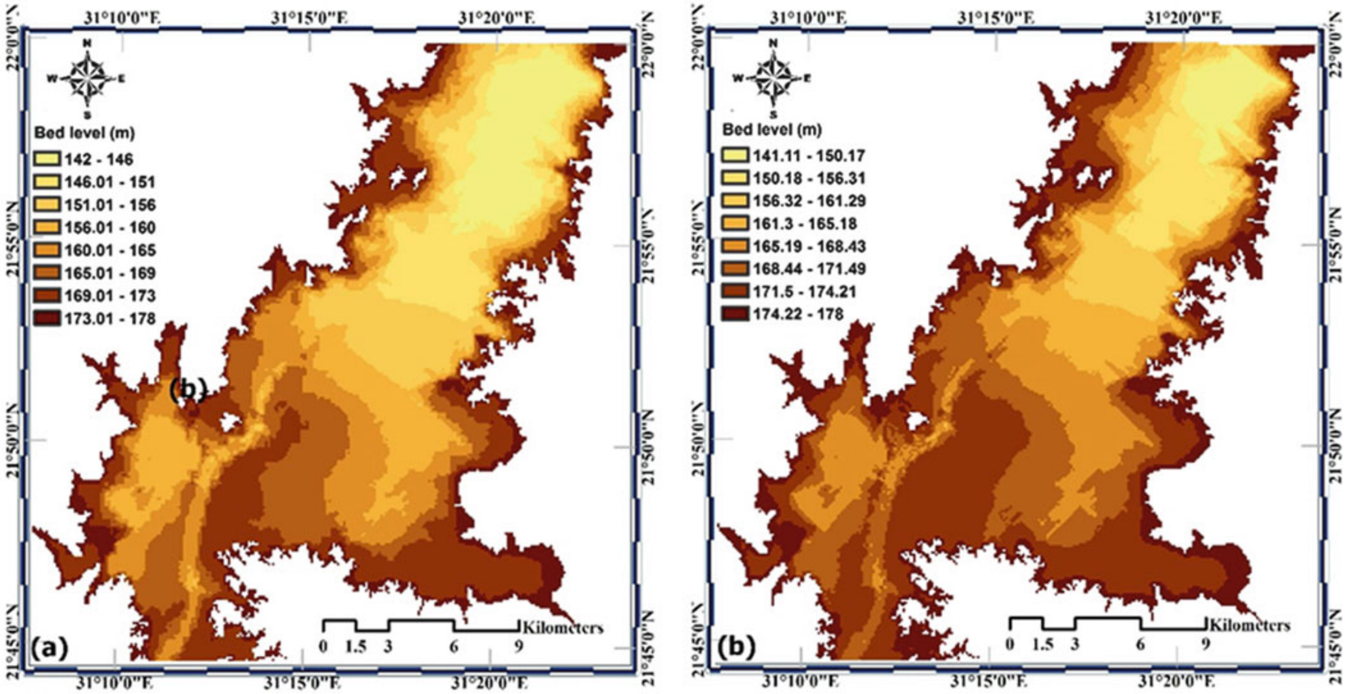

Fig. 16 The created bed surfaces of the study area: (**a**) The observed bed surface map for the year 2012 and (**b**) the modeled (predicted) bed surface map for the year 2012

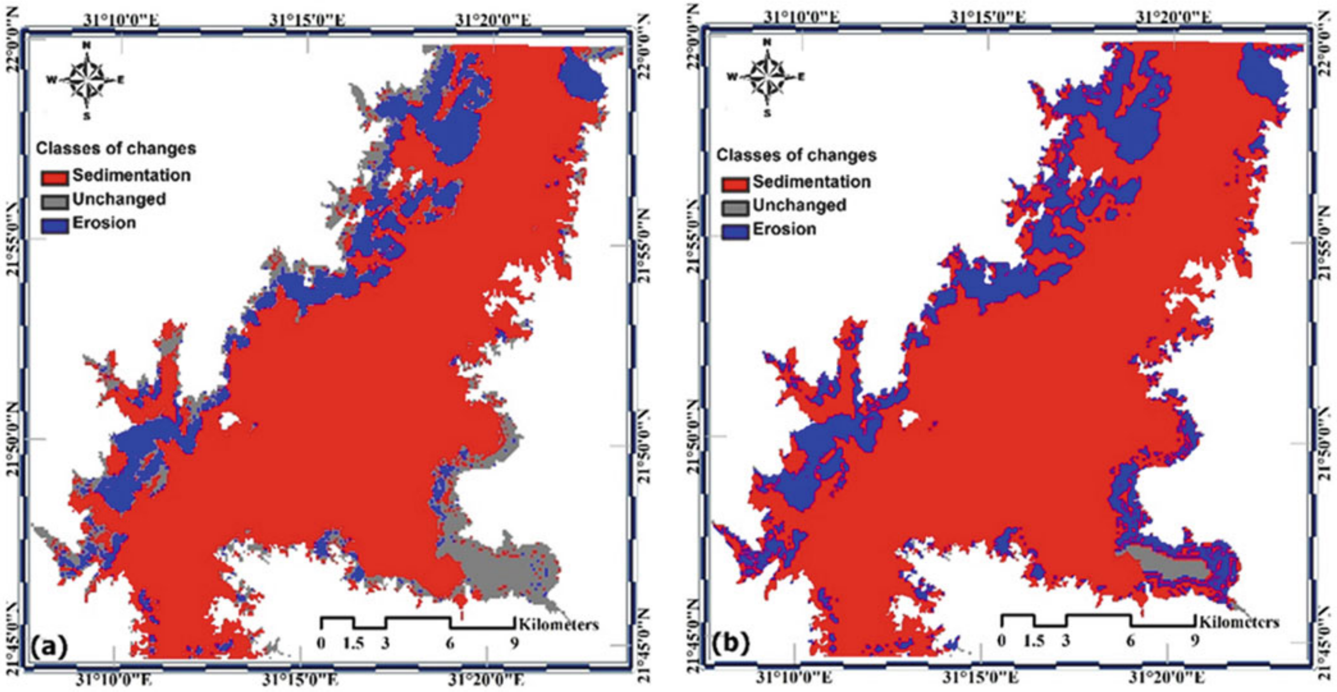

Fig. 17 Map of changes (a) observed for the period 1964–2012 and (b) modeled for the period 1964–2012

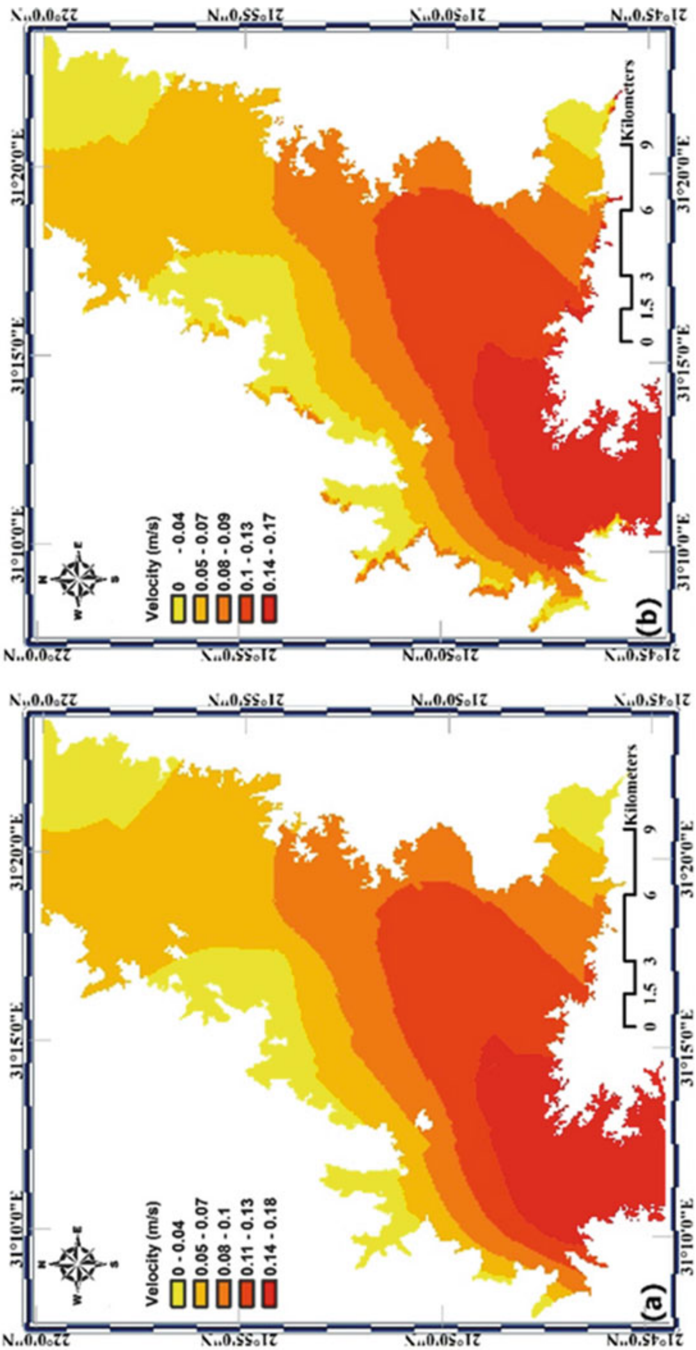

Fig. 18 Velocity distribution map (**a**) for the observed data in 2012 and (**b**) for the modeled measurements in 2012

5.3 Results of the Predicted Case Without GERD Operation

The results of this case can be summarized as follows:

The predicted bed surface map for the year 2020 and the map of changes between 1964 and 2020 are shown in Fig. 19. These maps are used to evaluate predicted sediment and erosion amounts in the study area at the year 2020 by their statistical analyses using ArcGIS software.

The predicted velocity distribution map for the year 2020 is shown in Fig. 20. This map is considered as an application for model prediction capability in predicting the velocity distribution through the study area after checking its accuracy for simulating the depth-averaged flow velocity distribution.

5.4 Results of the Applied Scenarios with GERD Operation

The results of the applied scenarios can be summarized as follows:

The bed surface maps for the years 2030, 2040, 2050, and 2060 are predicted for all applied scenarios. Maps in the years 2030 and 2060 produced from the first, second, and third scenario are shown in Figs. 21, 22, and 23, respectively, as sample results.

The maps of changes between 1964 and 2030, 1964–2040, and 1964 and 2050 and between 1964 and 2060 for all scenarios were produced. The predicted maps of changes between the first and the second scenarios are presented in Figs. 24 and 25, respectively, as sample results.

The created maps of changes from the year 1964 to the upcoming predicted years are used to detect the predicted amount of sediment and erosions in the years 2030, 2040, 2050, and 2060 by their statistical analyses using ArcGIS software.

6 Discussions

6.1 Discussions of the Model Accuracy

It is essential to check the accuracy of the model via the results of the calibration and verification processes. Therefore, the model was calibrated and verified using the necessary field data (average velocity distribution and bed levels) along two cross sections (sec.24 and sec.25), as shown previously in Fig. 3, and a longitudinal section that passes through the deepest points within the study area.

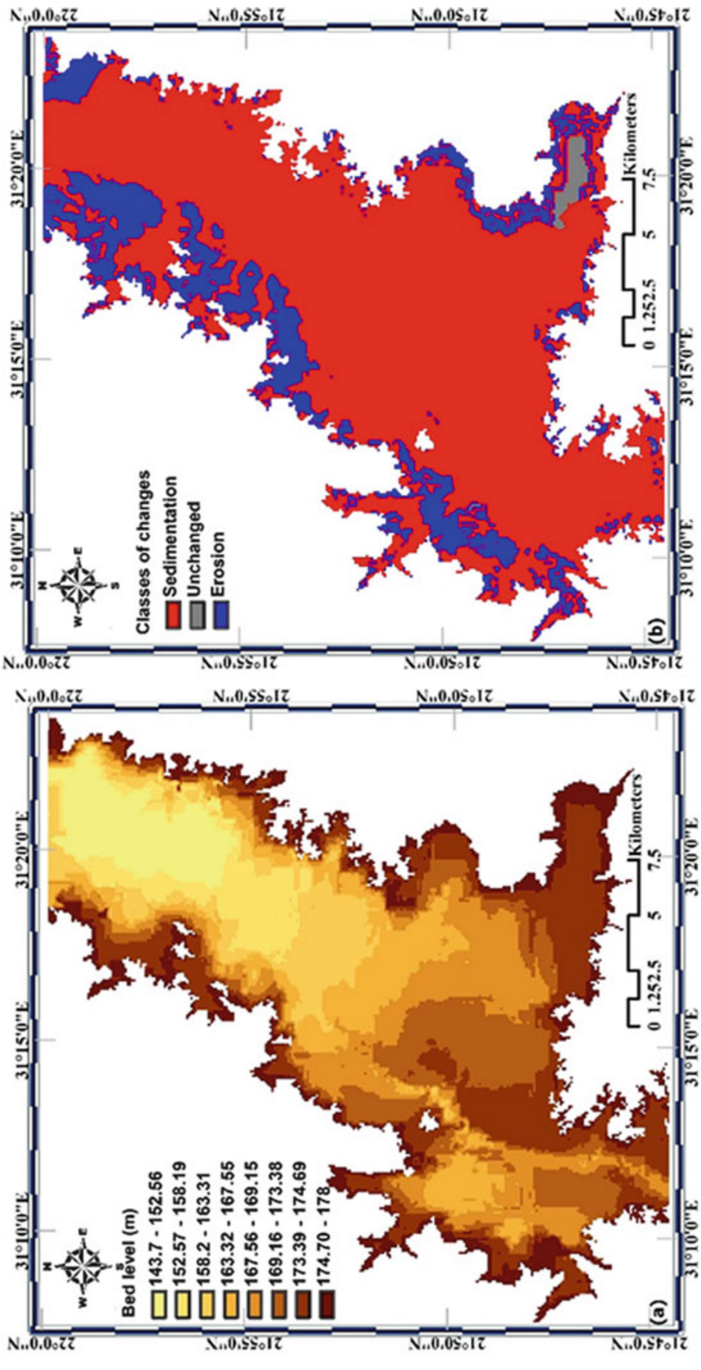

Fig. 19 The predicted maps of the study area without GERD: (**a**) 2020 bed surface map and (**b**) map of changes for the period 1964–2020

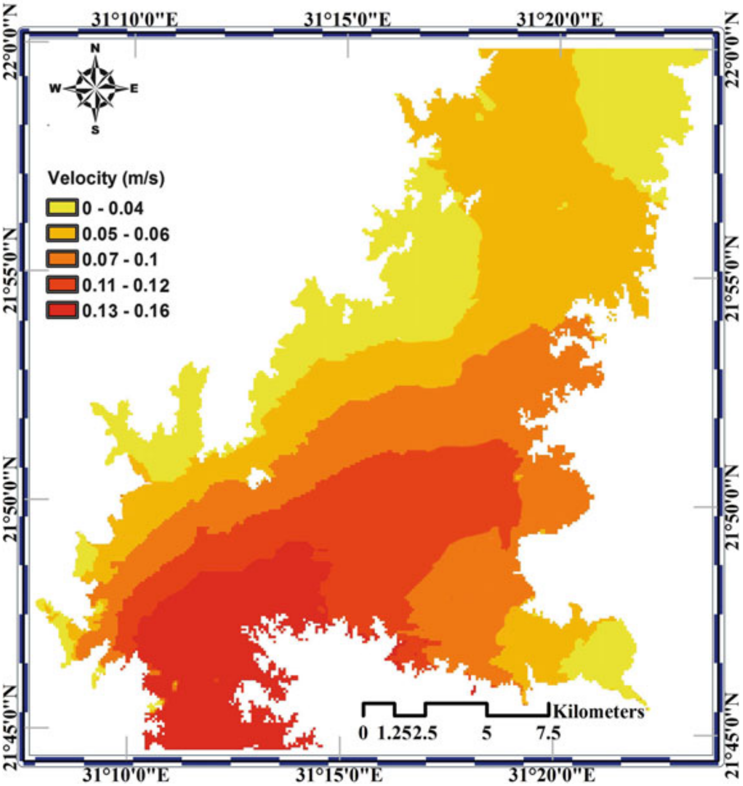

Fig. 20 The predicted velocity distribution map for the year 2020

6.1.1 Discussions of the Model Calibration

An example of both measured and modeled depth-averaged flow velocity profiles at the chosen each cross-section (sec.24 and sec.25) and the longitudinal section for the year 2008 (the reference case) are shown in Figs. 26, 27, and 28, respectively. It can be seen that there is an acceptable agreement between the model results and the field measurement for all sections.

To measure statistically the ability of the model as prediction tool, Fig. 29 shows a comparison between the measured depth-averaged velocities and the predicted ones for the year 2008; an acceptable agreement can be noticed. It can be said that the applied model is a useful tool for the simulation of depth-averaged flow velocities.

The bed levels at the year 2008 have been computed and compared to the field measurements at all sections. Three examples for the studied sections have been presented including cross section (24 and 25) and longitudinal section as shown in Figs. 30, 31, and 32, respectively. It can be noticed that there is an acceptable agreement between the model outputs and the field measurements for the different chosen cross sections and the longitudinal section.

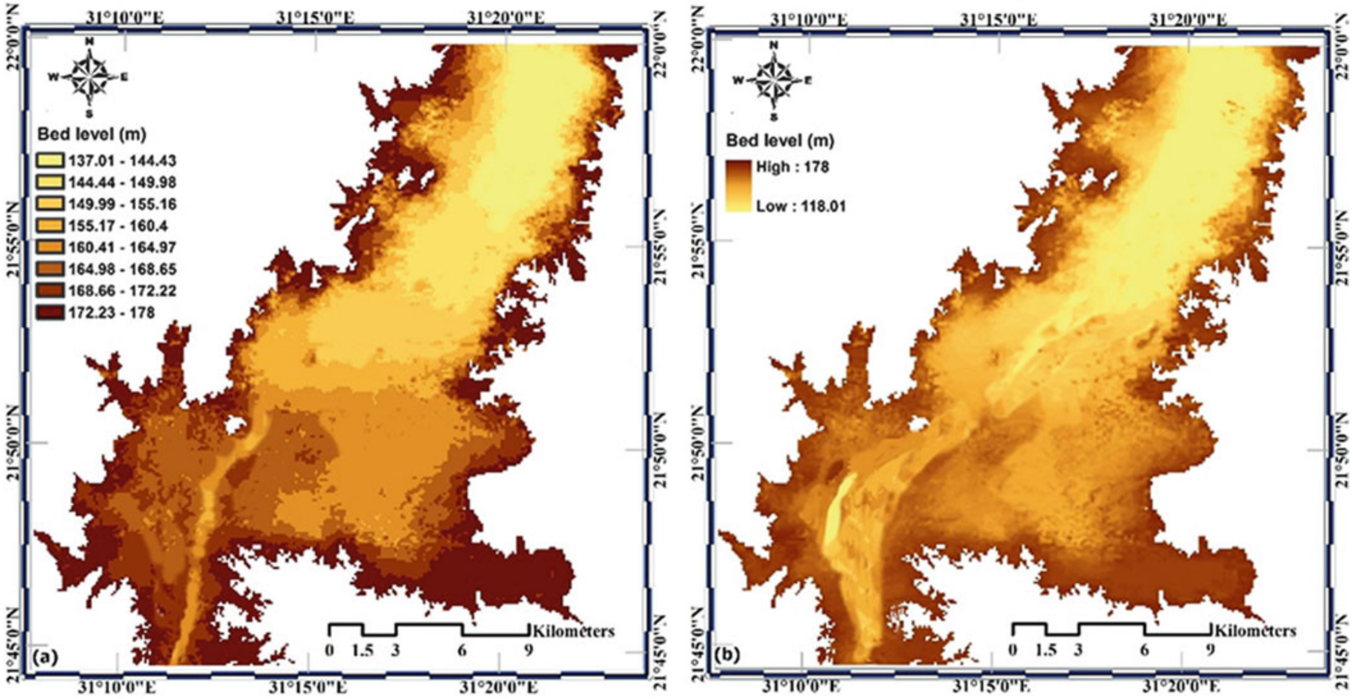

Fig. 21 The predicted bed surfaces of the study area from the first scenario: (**a**) 2030 bed surface and (**b**) 2060 bed surface

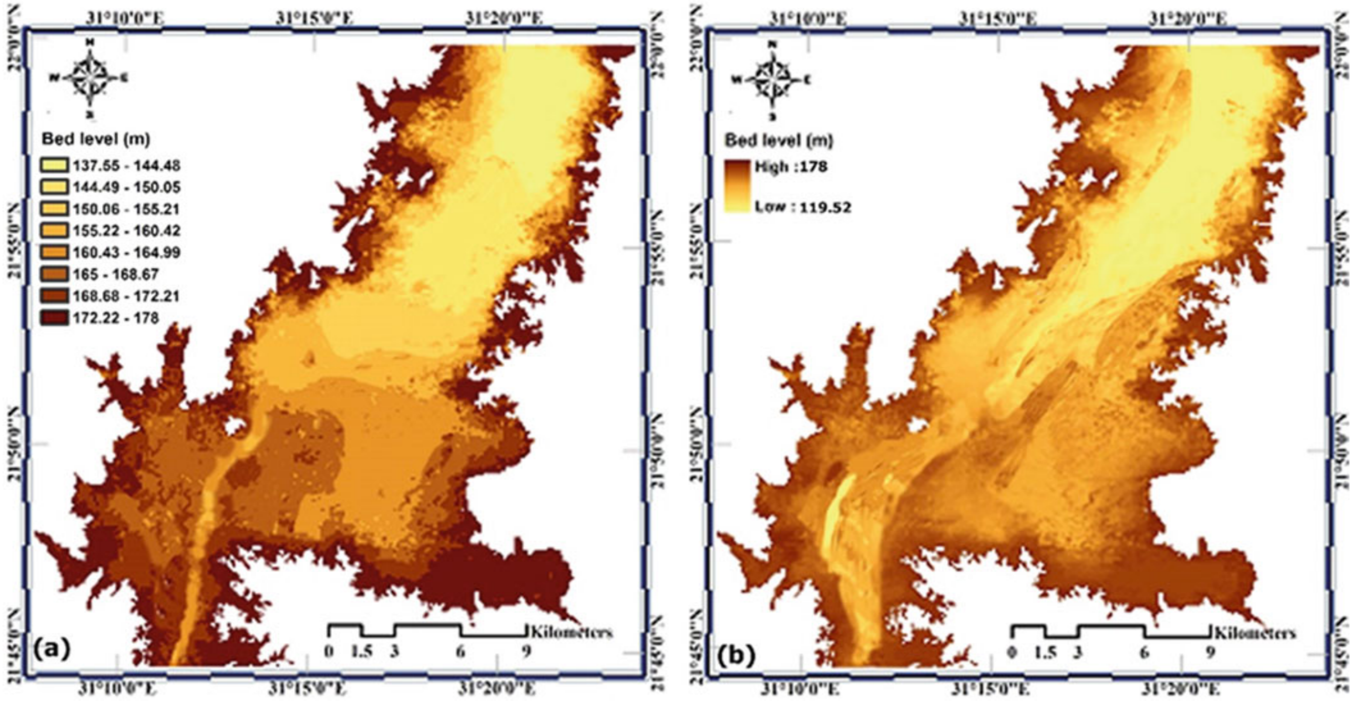

Fig. 22 The predicted bed surfaces of the study area from the second scenario: (**a**) 2030 bed surface and (**b**) 2060 bed surface

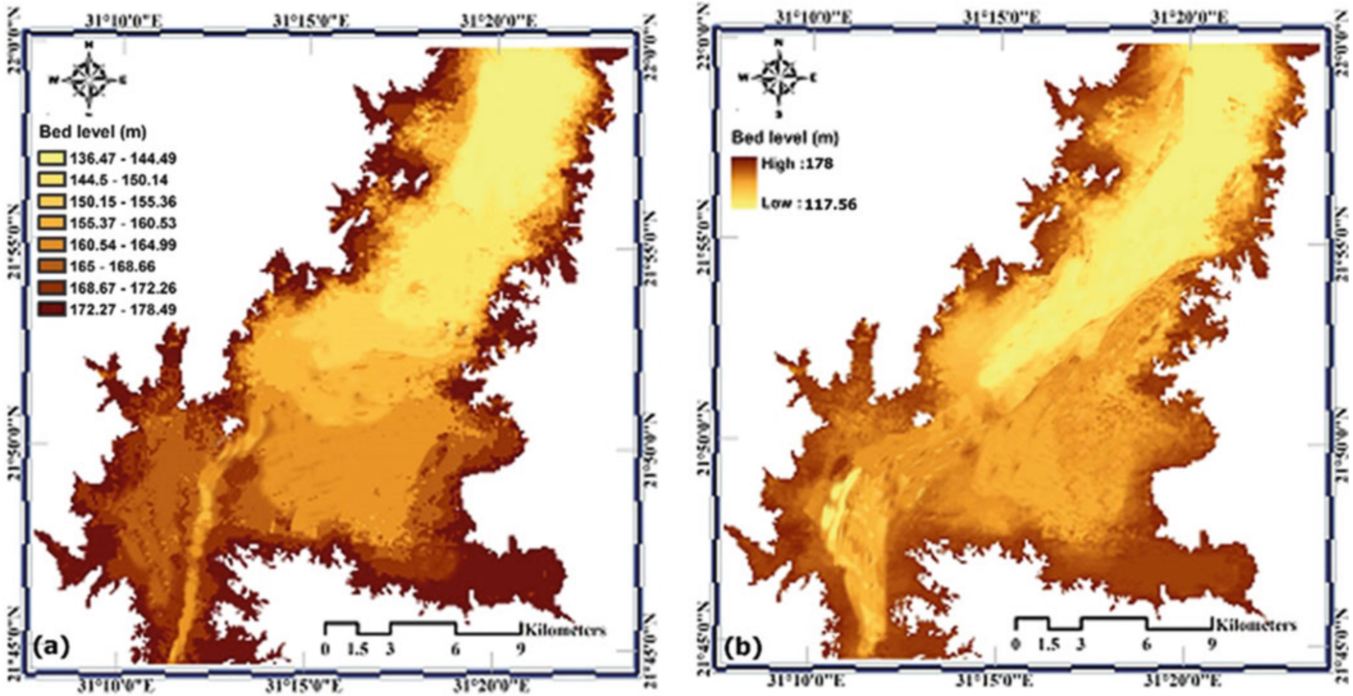

Fig. 23 The predicted bed surfaces of the study area from the third scenario: (**a**) 2030 bed surface and (**b**) 2060 bed surface

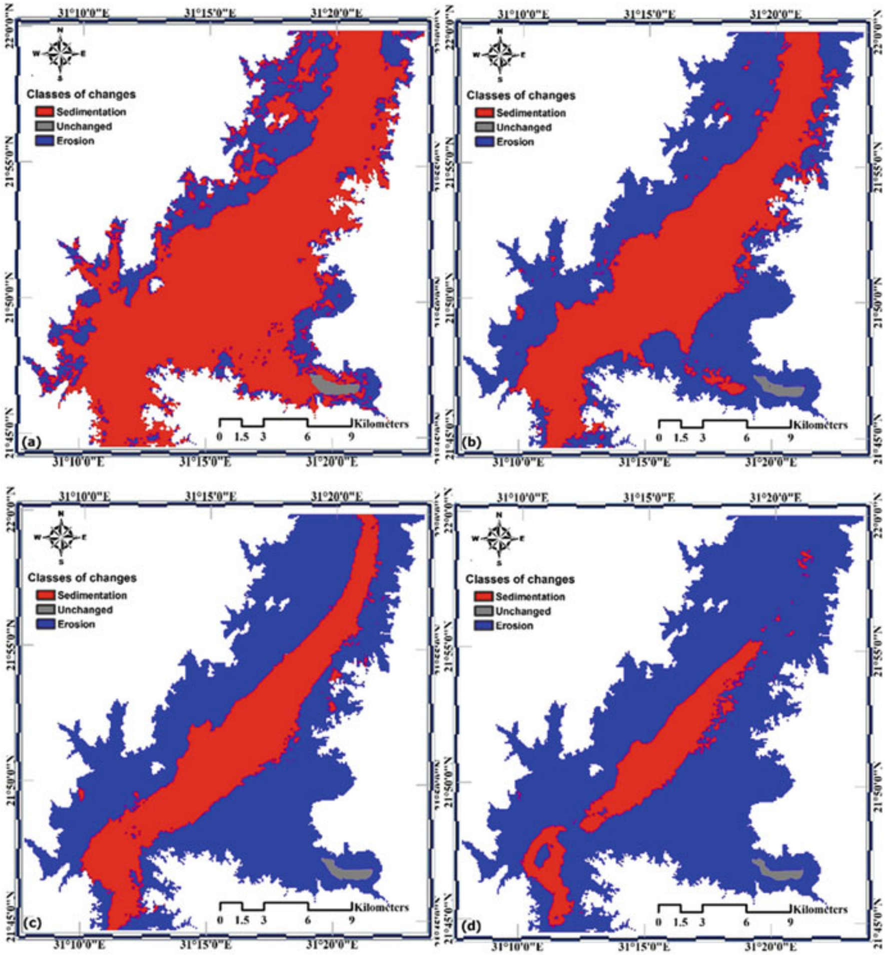

Fig. 24 Predicted map of changes from the first scenario (**a**) for the period 1964–2030, (**b**) for the period 1964–2040, (**c**) for the period 1964–2050, (**d**) for the period 1964–2060

Statistical analysis was performed via establishing a scatter diagram as shown in Fig. 33 to compare the (observed) bed levels and the predicted ones; an acceptable agreement can be noticed.

6.1.2 Discussions of the Model Verification

Figures 34, 35, and 36 show both measured and modeled depth-averaged flow velocity profiles at each chosen cross section (sec.24 and sec.25) and the longitudinal section for the year 2012 (the used year for model verification), respectively. According to these profiles; an acceptable agreement between the observed and

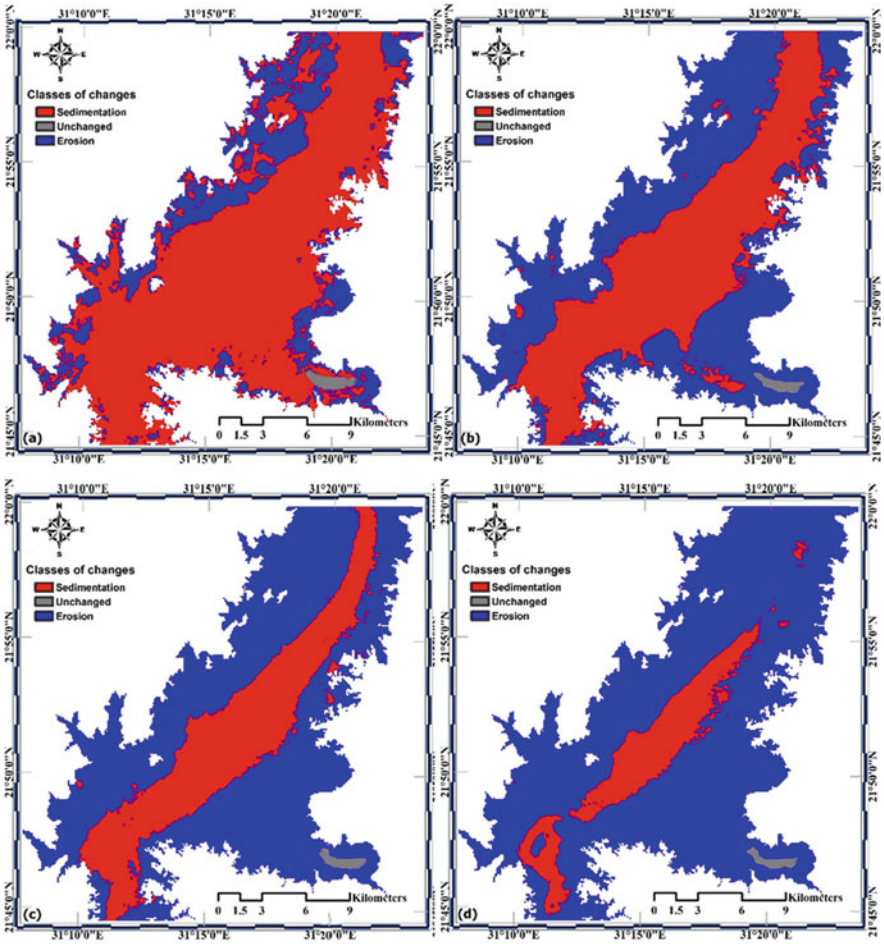

Fig. 25 Predicted map of changes from the second scenario (**a**) for the period 1964–2030, (**b**) for the period 1964–2040, (**c**) for the period 1964–2050, (**d**) for the period 1964–2060

modeled velocity results (profiles) for all sections although some slight differences are observed at sections 24 and 25. The error (difference) in general is very small compared to the measured average velocities in the lake.

Using statistical analysis principles, and based on both measured and predicted depth-averaged velocities, Fig. 37 shows a comparison between the measured and the predicted ones for the year 2012; a reasonable agreement can be noticed.

The bed levels for the year 2012 have been computed and compared to the field measurements at all sections. Three examples for the studied sections have been presented including cross section (24 and 25) and longitudinal section as shown in Figs. 38, 39, and 40, respectively. It can be noticed that there is an acceptable agreement between the measured and predicted (modeled) cross sections, and the

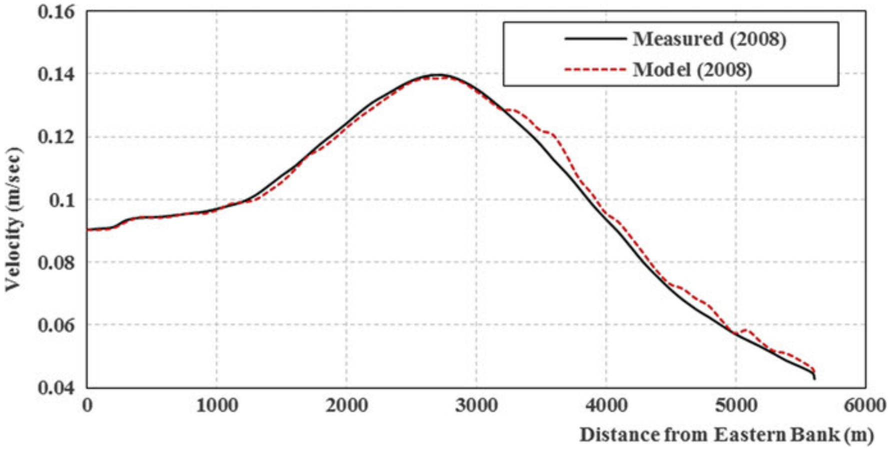

Fig. 26 Comparison between modeled and observed (measured) velocities through cross section 24 in the study area in the year 2008

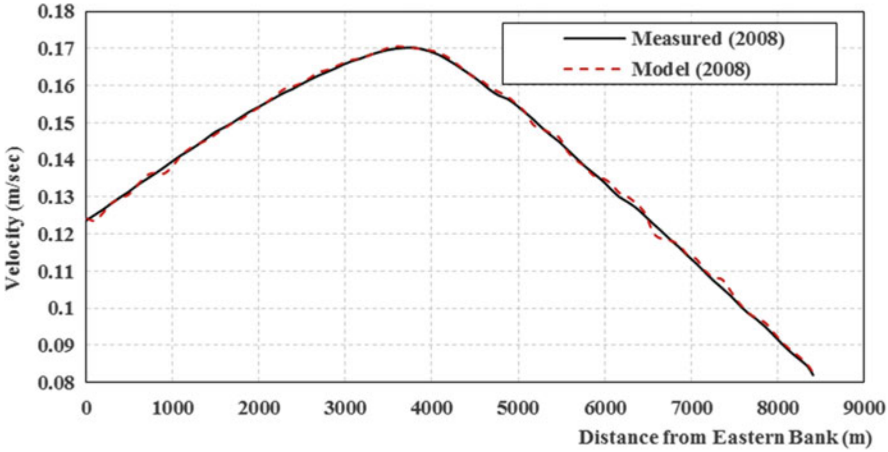

Fig. 27 Comparison between modeled and observed (measured) velocities through cross section 25 in the study area in the year 2008

longitudinal section was evident although some slight differences are observed at section 25 but can be neglected.

Statistical analysis was performed via establishing a graphical scatter diagram as shown in Fig. 41 to compare the (observed) bed levels and the predicted ones; a good agreement between the measured and predicted (estimated) bed levels was evident.

According to the values of statistical parameters, which deduced via the scattered plots in Figs. 29, 33, 37, and 41 and listed in Table 3, it can be found that the RT simulation model is well calibrated and considered an accurate tool to predict the future bed levels along the AHDL. The accuracy was more than 99% (R^2) for

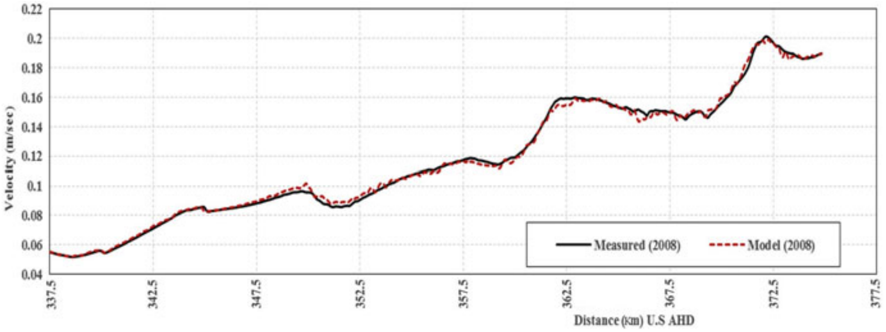

Fig. 28 Comparison between modeled and observed (measured) velocities through the longitudinal section in the study area's deepest points in the year 2008

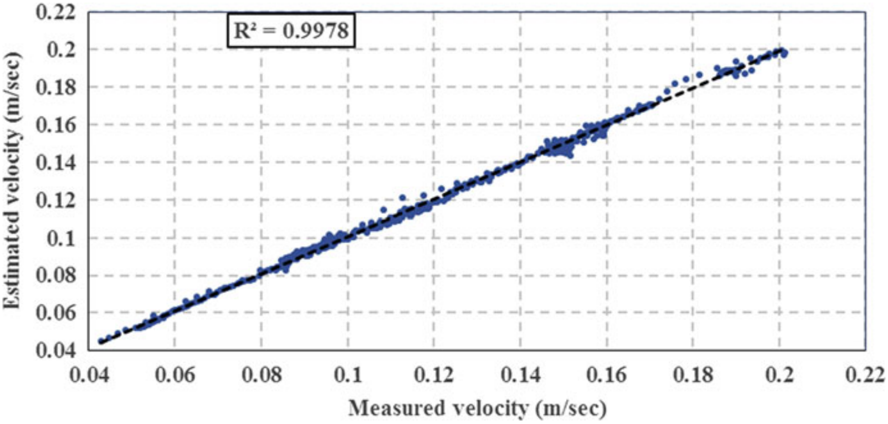

Fig. 29 Comparison between modeled and measured velocities in the year 2008

velocities and bed levels, respectively, between the model results and the field measurements at the chosen cross and longitudinal sections.

Above all, on the basis of the analysis of the model accuracy results, one can state that the model is well calibrated and well verified. Therefore, the model is capable of predicting the sediment amounts from the tested model scenarios.

6.2 *Estimation of Sediment and Erosion Without GERD*

Table 4 shows 2D surface area and amounts for the sediment and erosion categories from the year 1964–2008 and from the year 1964–2012 (observed and modeled cases), which were estimated by using the statistics of these change categories (classes) in the maps of changes of the study area shown in Figs. 14 and 17. The

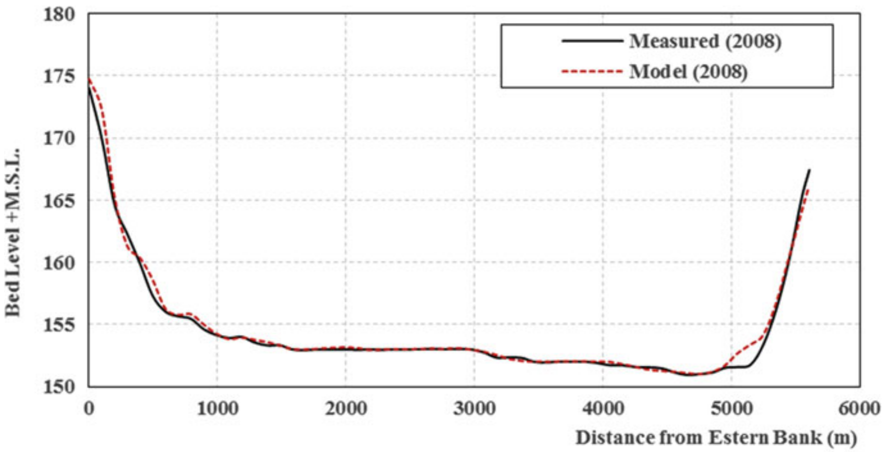

Fig. 30 Comparison between modeled and observed (measured) and modeled bed levels through cross section 24 in the study area in the year 2008

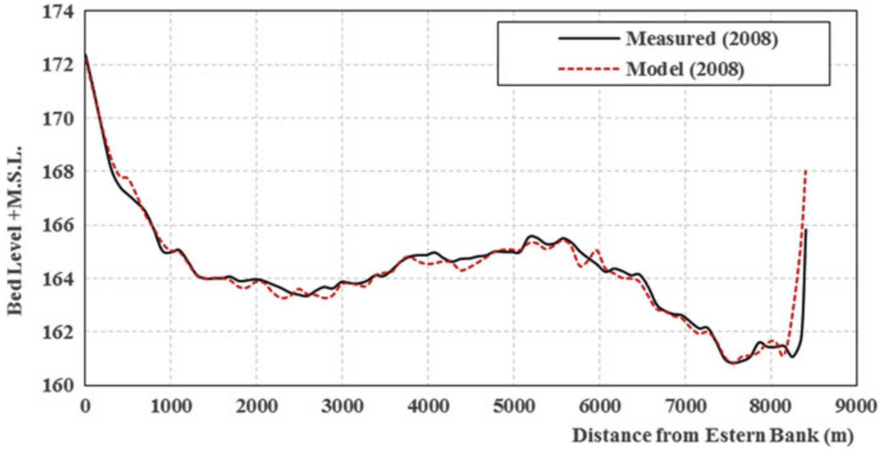

Fig. 31 Comparison between modeled and observed (measured) and modeled bed levels through cross section 25 in the study area in the year 2008

bit difference in the amount and 2D surface areas of both sediment and erosion, as it is obvious from this table [the maximum difference is less than 1% for the year 2008 (calibrated year) and less than 2.5% (verified year)], indicates that there is an acceptable agreement between the model outputs and the field measurements (the model is well calibrated and well verified). Therefore, the applied model is considered an effective tool for predicting sediment and erosion amounts in lakes.

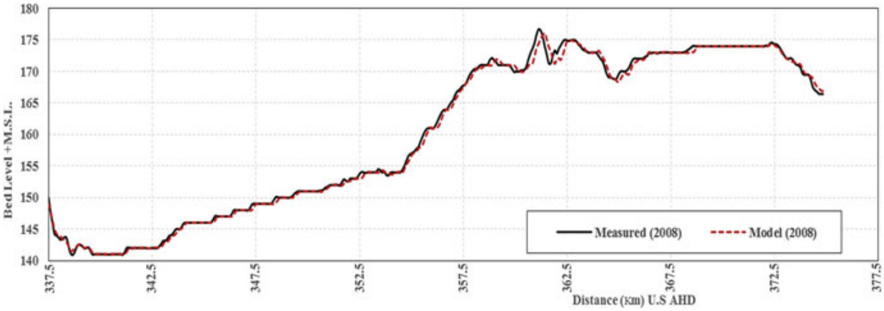

Fig. 32 Comparison between modeled and observed (measured) bed levels through the longitudinal section in the study area's deepest points in the year 2008

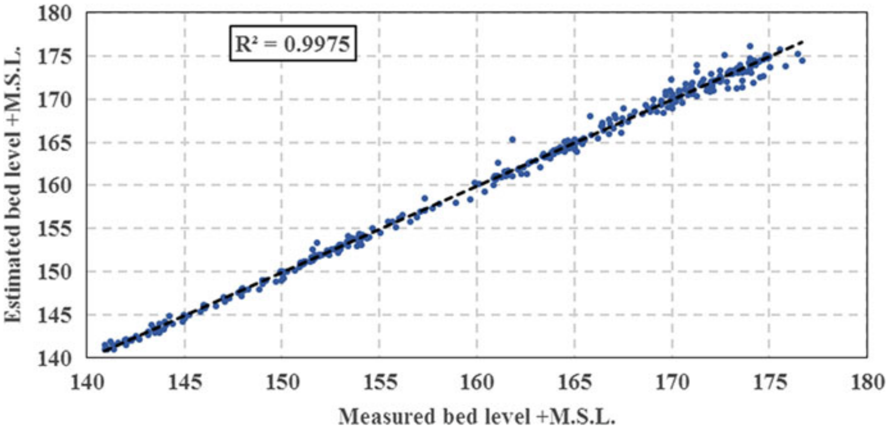

Fig. 33 Comparison between modeled and measured bed levels in the year 2008

6.3 Comparisons Without GERD

Table 5 illustrates that the total amount of sediment from the year 1964 to measured and modeled 2008 was about 4.254 and 4.255 billion m^3, respectively, and the estimated sediment amount by AHDA (the traditional cross-sectional method which is taken as reference method when the results are compared) was equal to 4.043 billion m^3 in the same period [17]. This means that the modeled computations overestimate the sediment capacity by about 5.24% compared to the method used by AHDA. In addition, the modeled computations of sediment amount from the year 1964 to modeled 2012 overestimate the sediment capacity by about 5.44% compared to the method used by AHDA. These low percentages indicate that the applied model is considered a useful and trustful tool for predicting the amount of sediment in the study area.

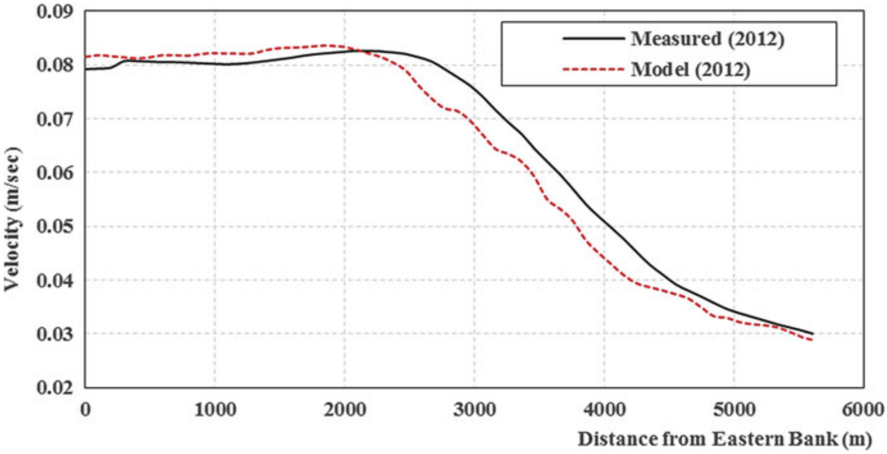

Fig. 34 Comparison between modeled and observed (measured) velocities through cross section 24 in the study area in the year 2012

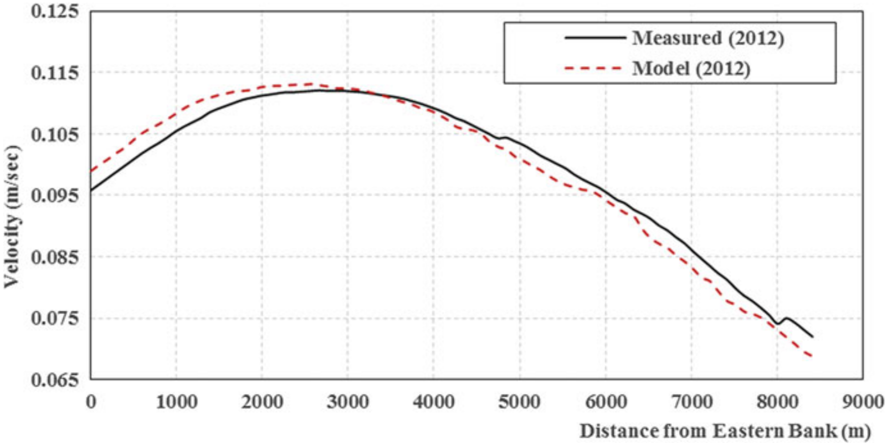

Fig. 35 Comparison between modeled and observed (measured) velocities through cross section 25 in the study area in the year 2012

6.4 Discussions of the Predicted Sediment and Erosion After GERD Operation

Table 6 shows predicted change in sediment and erosion amounts from the year 1964 to the upcoming year 2020 that was estimated by using the statistics of the change categories (classes) in the predicted maps of changes shown in Fig. 19b. Table 7 shows predicted changes in sediment and erosion amounts from the year 1964 to the upcoming years 2030, 2040, 2050, and 2060 that were estimated by using the

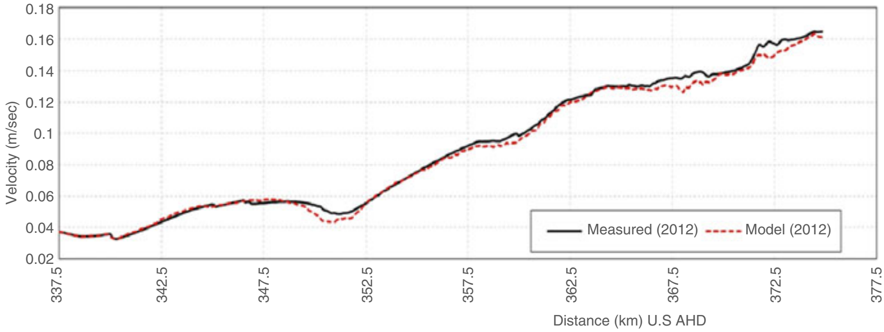

Fig. 36 Comparison between modeled and observed (measured) velocities through the longitudinal section in the study area's deepest points in the year 2012

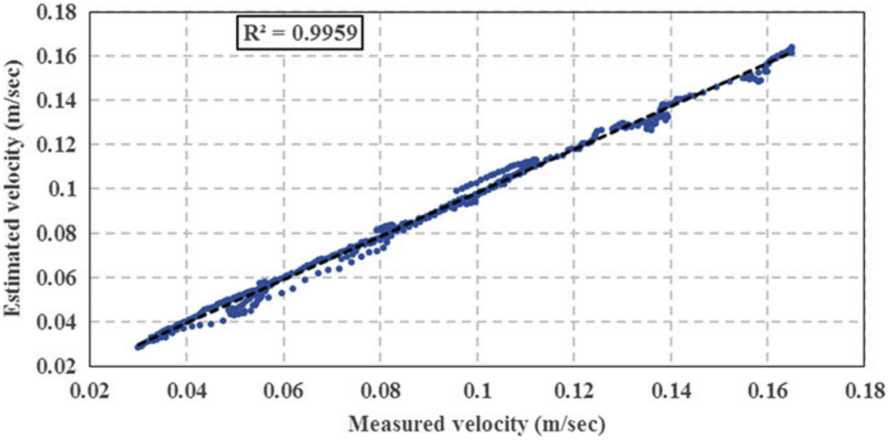

Fig. 37 Comparison between modeled and measured velocities in the year 2012

statistics of the change categories (classes) in the predicted maps of changes from the tested scenarios. It is evident from Tables 6 and 7 that there is a consequent decrease in the amount of sediment in all the studied time periods for the four tested scenarios from the years 2020–2030, 2030–2040, 2040–2050, and 2050–2060 accompanied with a consequent increase in the amount of erosion in the same periods.

Table 8 shows the predicted time serious reduction in the amount of sediment every 10 years in the period from the year 2020 to the year 2060 for all tested scenarios. It is clear from this table that the huge reduction will happen from the year 2030 to the year 2040. Contrary, the smallest reduction in sediment amount will occur in the period 2050–2060 as in this period the cross-sectional area of the study area as well as the 2D areas will be quite small (narrow shape) as shown in Figs. 36, 42, 43, and 45. Therefore the estimated reduction in the sediment capacity (predicted reduction in the amount of sediment) will be smaller. Also, this may be because most

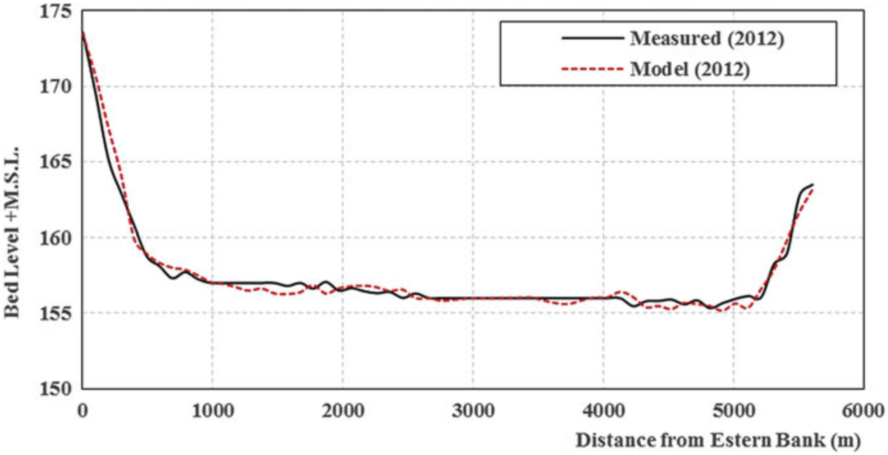

Fig. 38 Comparison between modeled and observed (measured) and modeled bed levels through cross section 24 in the study area in the year 2012

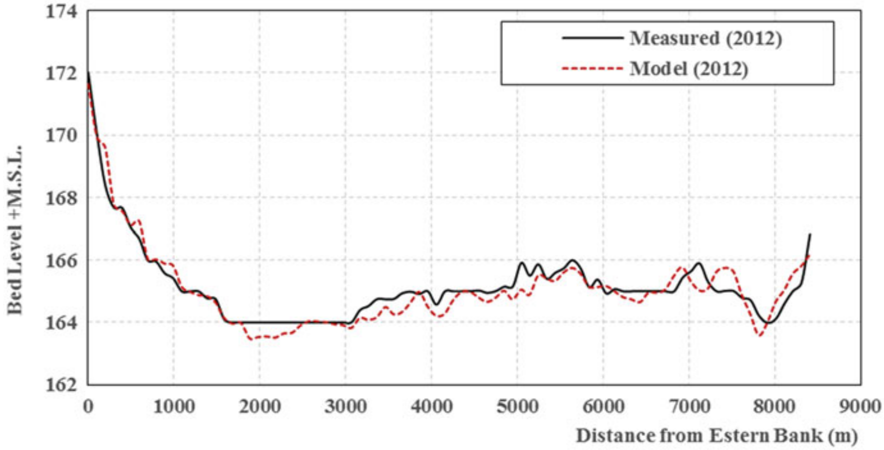

Fig. 39 Comparison between modeled and observed (measured) and modeled bed levels through cross section 25 in the study area in the year 2012

of the fine sediment are washed out or moved toward the downstream side through the previous years.

Table 9 illustrates the total predicted change (reduction) in sediment amounts until the years 2030, 2040, 2050, and 2060 for the four tested scenarios compared to the estimated amount of sediment of the study area in the year 2020. It is seen from Table 9 that about quarter of the accumulated sediment in the study area since the beginning of storage in the AHDL in the year 1964 will be lost from the active sedimentation zone. The sediment is expected to move from active sedimentation portion of Lake Nubia toward the AHD to be deposited in the dead zone of Lake

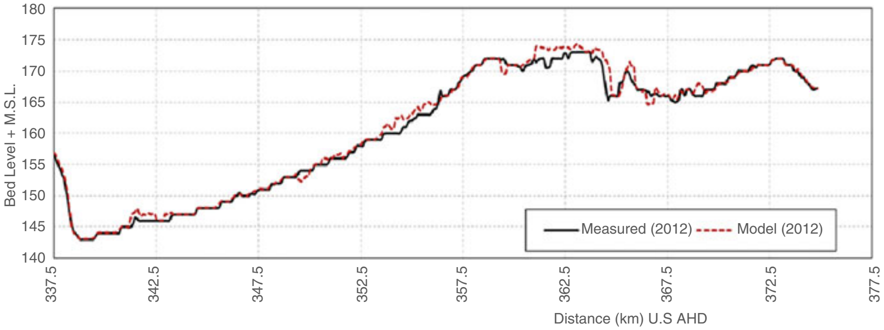

Fig. 40 Comparison between modeled and observed (measured) bed levels through the longitudinal section in the study area's deepest points in the year 2012

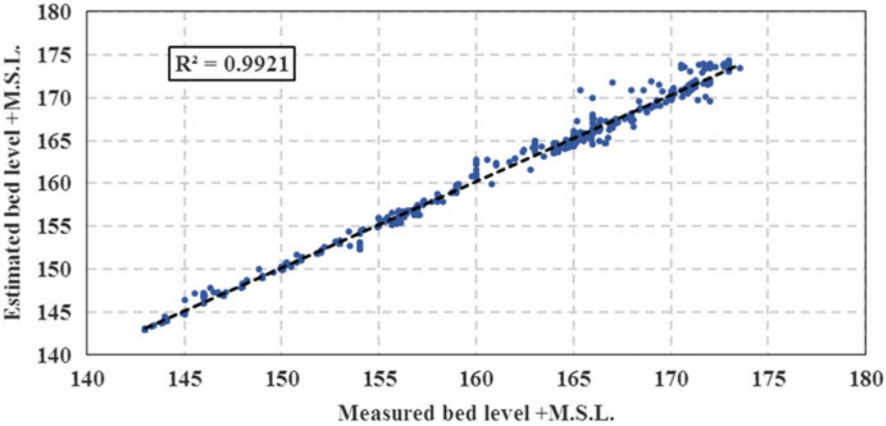

Fig. 41 Comparison between modeled and measured bed levels in the year 2012

Table 3 The statistical parameter values for model calibration and verification

		Depth-averaged velocities		Bed levels	
Process	Parameter	Value	Percentage (%)	Value	Percentage (%)
Model calibration	RMSE	0.002 (m/s)	2.57	0.55 (m)	2.90
	R^2	0.9978	99.78	0.9975	99.75
Model verification	RMSE	0.003 (m/s)	4.98	0.84 (m)	4.66
	R^2	0.9959	99.59	0.9921	99.21

Nasser after the year 2020. Moreover, it is clear that in the year 2060, there will nearly be full dissipation in the accumulated sediment amount in the study area (the reduction in the amount of sediment is more than 90%).

Table 4 Quantitative analysis of sediment and erosion from the year 1964 to the reference year 2008 and from the year 1964 to the year 2012 (modeled and measured results)

Quantitative characteristics	Year 2008 (measured)	Year 2008 (modeled)	% difference	Year 2012 (measured)	Year 2012 (modeled)	% difference
2D area of sediment (km^2)	282.06	282.02	0.01	315.81	318.62	0.90
2D area of erosion (km^2)	69.14	69.71	0.82	45.81	45.32	1.07
Amount of sediment (B.m^3)	4.254	4.255	0.02	4.762	4.881	2.49
Amount of erosion (B.m^3)	0.179	0.178	0.56	0.160	0.157	1.88

Table 5 Comparison of results between the present approach and the traditional method of estimating sediment amount

Time period	Computed amount of sediment (using measured data) (B.m^3)	Modeled amount of sediment (using model results) (B.m^3)	Amount of sediment by AHDA method (B.m^3) [17]
1964–2008	4.254	4.255	4.043
1964–2012	4.762	4.881	4.629

Table 6 Quantitative analysis of the predicted sediment and erosion amounts in the period (1964 to 2020)

Time period	Amount of sediment (B.m^3)	Amount of erosion (B.m^3)
1964–2020	5.160	0.261

6.5 Characteristics of the Lake Bed

Figures 42, 43, and 44 show the bed profiles of the study area according to the first scenario at the years 1964, 2020, 2030, 2040, 2050, and 2060 for cross sections 24 and 25 and for the longitudinal section, respectively. Moreover, Figs. 45, 46, and 47 show the same profiles according to the second scenario as sample results for the predicted bed profiles of the study area from the applied scenarios. These profiles are deduced from the predicted bed surface maps (see sample results in Figs. 21, 22, and 23). The difference between every two profiles represents the predicted reduction in sediment depths (sediment thickness).

According to these profiles, it is evident that there was a variation in the reduction of sedimentation thickness reduction along the study area, and the maximum reduction thickness of sediment will occur between the year 2050 and year 2060. On the other hand, the minimum reduction in sedimentation depth is observed in the period from the year 2020 to the year 2030. In contrast, the minimum reduction will take place in the period 2020–2030. Moreover, it is clear that in the year 2060, the

Table 7 Quantitative analysis of the predicted sediment and erosion amounts from the tested scenarios

	Amount of sediment (B.m^3)				Amount of erosion (B.m^3)			
Time period	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)
1964–2030	3.794	3.829	3.778	3.826	0.276	0.275	0.288	0.275
1964–2040	2.376	2.437	2.339	2.413	1.342	1.298	1.654	1.311
1964–2050	1.083	1.209	0.996	1.148	3.598	3.377	3.850	3.488
1964–2060	0.324	0.514	0.195	0.414	5.888	5.312	5.997	5.622

Table 8 Reduction in the amounts of sediment in the study area due to GERD construction

Year	Time period	Reduction amount of sediment ($B.m^3$)				Reduction (%)			
		Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)
2020									
	2020–2030	1.366	1.331	1.382	1.344	26.47	25.80	26.78	26.05
2030									
	2030–2040	1.418	1.392	1.439	1.403	27.48	26.98	27.88	27.19
2040									
	2040–2050	1.293	1.228	1.343	1.265	25.06	23.80	26.03	24.52
2050									
	2050–2060	0.759	0.695	0.801	0.734	14.71	13.47	15.52	14.22
2060									

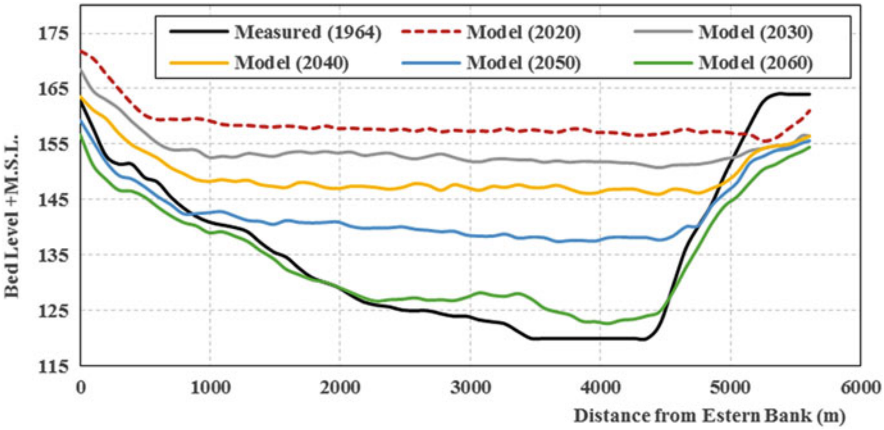

Fig. 42 The predicted bed profiles for cross section 24 from the first scenario

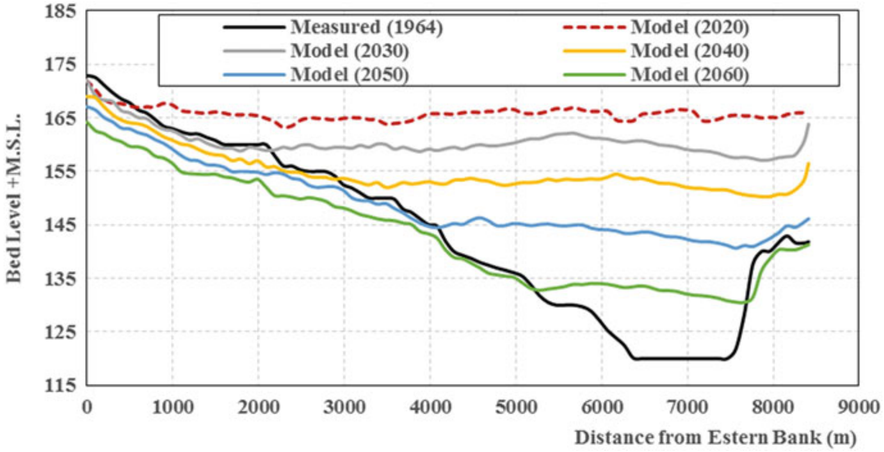

Fig. 43 The predicted bed profiles for cross section 25 from the first scenario

sediment strata will sufficiently appear in most of the study area and the amount of sediment will be quite negligible compared to that in the year 2020. According to the bed profile trends of the first scenario and the second one, it is clear that there was a slight increase in the predicted bed levels of the study area from the second scenario compared to the first scenario. Consequently, the computed amount of sediment by the second scenario was slightly more than the computed amount from the first scenario and vice versa for the erosion amount as indicated in Table 6. This explains that the difference in the computed amounts of sediment and erosion by the applied four scenarios, as shown in Table 6, is due to the change in the bed levels which is related to the change in the annual sediment rate and inflow velocity among these scenarios.

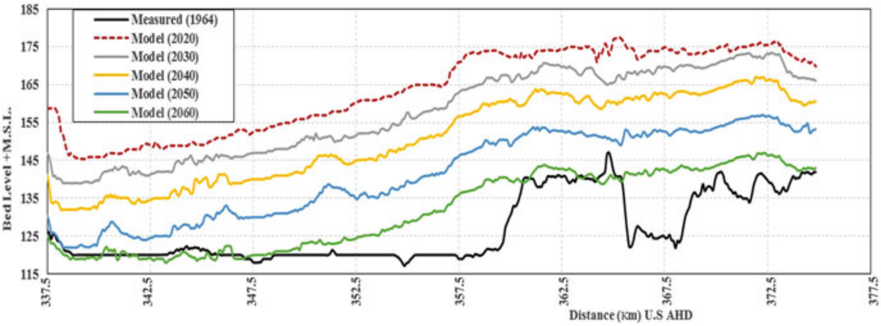

Fig. 44 The predicted longitudinal section bed profiles from the first scenario at the maximum sedimentation thickness of the study area

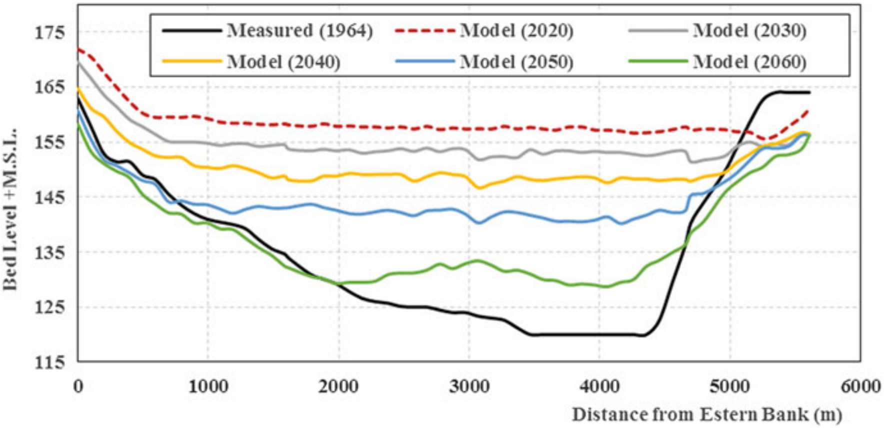

Fig. 45 The predicted bed profiles for cross section 24 from the second scenario

7 Conclusions

This chapter presents and discusses the results of applying, for the first time, the machine learning model (RTs) coupled with 3D GIS-based model for Lake Nubia to estimate and to predict the sediment amount in Lake Nubia upstream of AHD after GERD operation. For this purpose, four scenarios (reduction in inflow quantity by 5–10% and in annual sediment rate by 60–65%) are tested after the successful processes of model calibration and verification. The results indicated that there is an acceptable agreement between the model results and the field measurements for all sections where the values of RMSE% are 2.90 and 2.57 for bed levels and velocity, respectively, during calibration. While for verification, the values were 4.66 and 4.98 for bed levels and velocities, respectively. On the other hand, for calibration the values of R^2 were 0.9975 and 0.9978 for bed levels and velocity,

Table 9 Total reduction in the amounts of sediment due to GERD construction compared to the year 2020

	Total reduction in the amount of sediment (B.m^3)				Total reduction (%)			
Year	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)	Scenario (1)	Scenario (2)	Scenario (3)	Scenario (4)
2030	1.366	1.331	1.382	1.344	26.47	25.80	26.78	26.05
2040	2.784	2.723	2.821	2.747	53.95	52.78	54.66	53.24
2050	4.077	3.951	4.164	4.012	79.01	76.58	80.69	77.76
2060	4.836	4.646	4.965	4.746	93.72	90.05	96.21	91.98

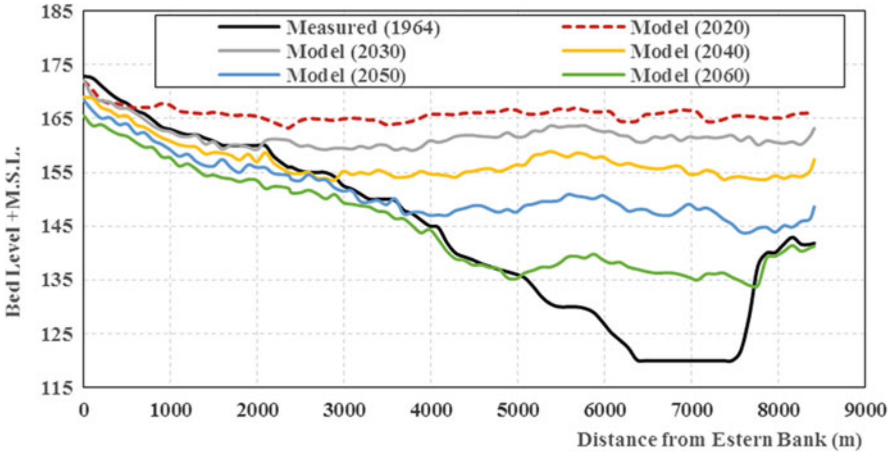

Fig. 46 The predicted bed profiles for cross section 25 from the second scenario

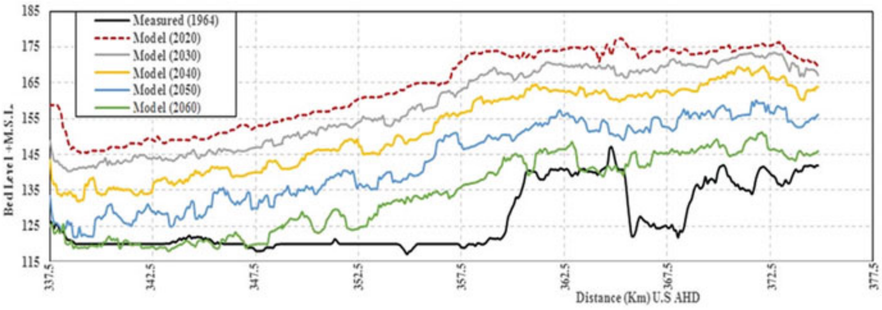

Fig. 47 The predicted longitudinal section bed profiles from the second scenario at the maximum sedimentation thickness of the study area

respectively, while for verification, they were 0.9921 and 0.9959 for bed levels and velocities, respectively. Consequently, it is concluded that the RT model is an effective tool in simulating and predicting both the bed levels and water velocities in the study area. The RT model overestimated the sediment amount by about 5.24 and 5.44% from the year 1964–2008 and from the year 1964–2012, respectively, compared to the results obtained by applying the cross-sectional method applied by AHDA. Moreover, the calibrated and verified model has been applied to predict the amount of sediment and erosion from years 1964 to 2020. For the tested scenarios, the calibrated model was used to predict the amount of sediment and erosion in the periods 1964–2030, 1964–2040, 1964–2050, and 1964–2060. The results showed that the study area might suffer from a consequent decrease in the amount of sediment from the year 2020 to the year 2060 and the decreased amount will be more than 90% of that in the year 2020. It means that the total amount of sediment deposited in the active sedimentation portion of AHDL will decrease by more than 90% from the year 2020 to the year 2060 moving toward Lake Nasser upstream the AHD.

8 Recommendations

The authors recommend conducting future studies about determining the effect of GERD under different expected operation policies on the accumulated sediment in the AHDL and the effect of these scenarios on the lifespan of the AHDL. Moreover, other future studies should be implemented to identify the impacts of the GERD on the water levels and their surface areas of the AHDL and consequently its impact on the hydropower generation from AHD. A proper mechanism should be investigated to use the moved fine sediment toward Lake Nasser.

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Part VI
Maximizing the Benefits of AHD Reservoir

Dredging the Clays of the Nile: Potential Challenges and Opportunities on the Shores of the Aswan High Dam Reservoir and the Nile Valley in Egypt

Baha E. Abulnaga

Contents

Abstract The Aswan High Dam (AHD) Reservoir has become a major storage for sediments over the last 50 years. The southern part in Sudan called Lake Nubia is heavily silted and is developing a new delta. The construction of the Great Ethiopian Renaissance Dam (GERD) is expected to retain an important volume of silt and lower the levels of the water in the AHD Reservoir during fill-up. The impact is a reduction of the storage capacity in Sudan and Egypt, but the silver lining is an opportunity for development of small communities through dredging and the construction of onshore sediment ponds that can be turned into farm land.

The large accumulation of clays requires a special approach for dredging. Lake Nasser, clay fractions can range from 30 to 90% of the sediments in Egypt, after that the coarse material had deposited in Lake Nubia in Sudan. For the fraction smaller than 0.42 mm, its plasticity index is used as measure of the tendency to form balls of clay – which would slow greatly dredging efforts. There is a dearth of data on the plasticity index of clays from the AHD Reservoir, but comparative studies can be done at Kalabsha, 50 km south of Aswan, at Aswan, Toshka, Qena, as 2% of the

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sediments mostly clays manage to pass through the AHD. At AHD Reservoir, they are composed of a large portion of smectite (~70%), kaolinite (<25%), and illite (<10%) particularly in Lake Nubia. Illite is typically of volcanic origin. The new delta forming within the Aswan High Dam Reservoir contains high portions of kaolinite through the erosion of the shores and from wind-transported material. Kaolinite-rich sediments reach 50% of the central and northern sections of Lake Nasser in Egypt.

While high plasticity index is a challenge to dredging, it is a positive property for building dykes around sediment ponds, quick formation into impermeable layers to prevent seepage of water, and the manufacture of bricks and for a local ceramic industry. Balls of clays sediment much faster than particles of clay and would cut down the size of settling ponds for farming.

To simulate the potential problems in Egypt, samples of natural clay sediments were dredged in the USA and sent to the slurry lab of Splitvane Engineers. Samples with a plasticity index of 32% were tested at a different velocity from 1.4 to 5.8 m/s and over different periods of time to simulate pumping over 8 km. No similar ablation wheel was found in Egypt or Europe at the time of writing this chapter. The results of lab tests are presented to understand the potential challenge of dredging the clays of the AHD Reservoir and should be repeated on samples from the Nile sediments by building a dedicated testing facility in an Egyptian Research Institute. These natural clays showed a different degradation rate than previous tests conducted by the USACE on synthetically composed clays. The degradation was dependent on properties of the sample, the tangential velocity of the drum, and the distance of pumping. These tests should be repeated on samples from the AHD Reservoir for better planning the development of new ceramic industries and small communities.

Keywords Ablation tests on clay, Ball clays, Balls of clay, Ceramic industries, Clay, Dredging, Egypt, Kaolinite, Liquid limit, Plasticity index, Smectite

1 Introduction

For thousands of the years, the Nile has deposited alluvium in Egypt and discharged it into the Mediterranean Sea on the shores of Palestine and the Levant, bringing wealth and prosperity. The Ancient Egyptians expressed their gratefulness by inventing a divinity for the Nile.

In 1964, the situation started to change dramatically with the construction of the Aswan High Dam (AHD) Reservoir. Upstream of the AHD, the sediments start to deposit at the Roseires Reservoir in Sudan. Once the balance reaches Lake Nubia at the Second Cataract, they deposit into a new delta. These two locations act as a sort of filter, catching sand and silt. Although clay is very fine with a mean diameter of 2 μm, there is evidence that nature causes some flocculation through changes to an organic fraction. Flocculated clays sink at the Roseires Reservoir and in Lake Nubia, but the rest continues to migrate north into Egypt.

Most sediment that Egypt receives is therefore clays. It is estimated that 2–2.6 million tons or 2% of the sediments reaching Lake Nubia manage to pass through Aswan into Qena and should reach Cairo by 2050.

These clays are classified as medium to high plasticity. Viewed as a calamity for structural engineers in search for rocky foundations to build new skyscrapers on the shores of the Nile, they are in reality a blessing for a new industry of ceramics and bricks or for stabilizing poor desert soils.

High-plasticity clays are a challenge to hydrotransport as they consume more energy than slurry material. However, their ability to preserve shape as balls of clays makes them ideal for building banks, settling ponds, and new canals as they form an impermeable layer.

In this chapter, the characteristics of Egyptian clays are examined. In the absence of data on naturally dredged medium plasticity clays, some tests were conducted on samples dredged in Houston at a plasticity index of 32%.

2 Distribution of Clays Along the AHD Reservoir and Nile Valley in Egypt

There are three aspects for dredging sediments from the Aswan High Dam Reservoir and the valley of the Nile:

- Coarser material, sand, and silt have been accumulated at 98% in Lake Nubia, Sudan.
- Fine materials, mainly clays, are transported north, past Aswan into the valley of the Nile at the rate of 2% of the sediments coming from the AHD.
- A mixture of clays and fine sands form in the Egyptian AHD Reservoir section by a combination of wind-transported material and erosion of the shores of Lake Nasser.

Estimated annual accumulation of sediments since 1964 ranges from 110 million cubic meters [1] to 135 million cubic meters [2, 3]. Large islands are forming near the Second Cataract where 25 m of the depth has been filled up with sediments. This phenomenon is called the new delta, a way for the powerful Nile River to correct man's intervention on its course. A similar phenomenon occurs in the USA with the Mississippi that changes its course through the years as parts of sediments and new channels open up.

The total accumulated sediments from 1964 to 2017 are therefore 5.83 km^3 or 5.83 billion cubic meters based on 110 million cubic meters per year to 6.63 km^3 or 6.63 billion cubic meters based on 135 million cubic meters per year.

The construction of the Great Ethiopian Renaissance Dam (GERD) is likely to trap the coarser material, but would not be successful at trapping clays with a diameter of 2 μm.

Currently, the Roseires Reservoir in Sudan acts as the first trap for sediments coming from Ethiopia. Omer et al. [4] developed a model for sedimentation in Roseires.

Most sediments that have accumulated since 1965 [5] have been south of the Egypt-Sudan border but are now moving north into Lake Nasser (see Fig. 1). The new delta forming is mostly in Lake Nubia [7]. Unless joint ventures and agreements are established between Egypt and Sudan to dredge Lake Nubia, material dredged in Lake Nasser will remain extremely rich in very fine particles and clays. Complex geopolitical problems have prevented such agreements between the two countries, such as the very long civil war in Sudan that ended up splitting the country into two new nations in the north and the south of Sudan.

Said [1] and Abulnaga and Abdel-Fadil [6] discussed the movement of the sediments as a result of the construction of the Aswan High Dam and presented evidence that the clays continue to move north past the new delta being formed in Lake Nubia. Farhat and Salem [8] completed a particle size distribution of the sediments of the AHD. The main channel sediments tend to be silty clay and clayey silt, while eastern and western banks tend to contain more sand and some gravel with deposits being accentuated by movement of sand dunes from the desert. Fines tend to become smaller in size with depth. They cited a number of studies by previous authors. Aspects of the sedimentation in the Aswan High Dam Reservoir were summarized as:

- Depth of the sediments at the entry to Lake Nubia at Gomi was already 17 m in 1977.

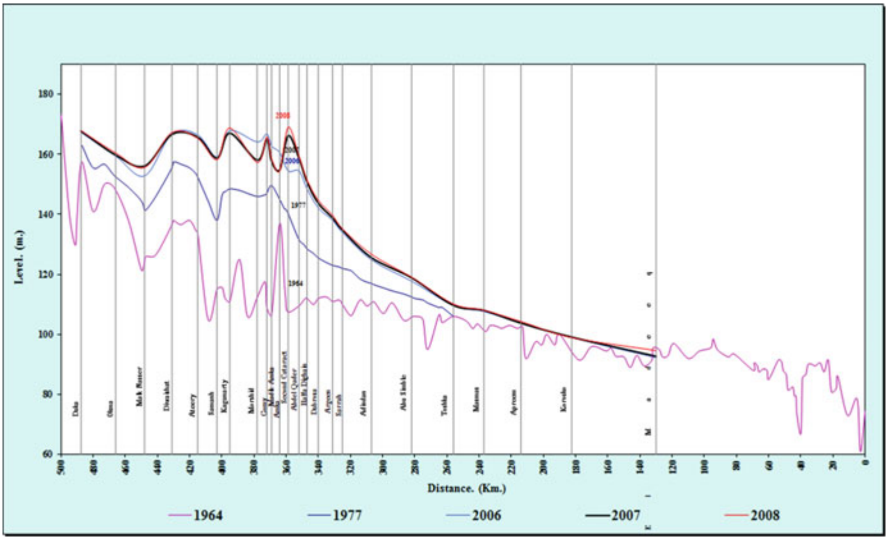

Fig. 1 Accumulation of sediments and formation of the new delta in Lake Nubia and Lake Nasser – reproduced and updated after Abulnaga and Abdel-Fadil [6]

- Depth of the sediments at Abacal on the Second Cataract was already 20 m in 1977.
- Depth of the sediments at Adinban, further downstream, was 2 m in 1977.
- Depth of the sediments at Abu Simbel was 1 m in 1984.
- Ninety percent of the sediments deposited between 1964 and 1987 were in the Sudanese part of the reservoir, or Lake Nubia.
- Microorganism developed and acted as filtering mechanism by digesting organic material carried by fines causing coagulation of clays into larger particles that tended to sink and prevent turbid waters from reaching Aswan.

The morphology will change with the construction of the GERD [9]

Dredging the sediments in the Egyptian part of the Aswan High Dam Reservoir and their transportation in a slurry form [2, 6, 10] involves moving fines and clays at a much higher percentage than dredging near the Second Cataract in Sudan. Therefore, future projects for the development of small communities in Egypt should put an emphasis on the clayish sediments. If such communities are built closer to Aswan, they would have access to electric power.

The principal challenge for hydraulic dredging is the high plasticity index of clays. There is currently no definite map for the plasticity index of Egyptian sediments in the AHD Reservoir or Nile Valley in Egypt. Data must be extracted from a large number of published papers but ultimately require testing.

It is critical and recommended to test for the liquid limit (L_L) and the plastic limit (P_L).

The liquid limit is defined as the moisture content in soil above in which it starts to act like a liquid or act as a slurry mixture and below in which it acts as plastic. To conduct a test, a sample of clay is thoroughly mixed with water in a brass cup. The number of bumps required to close a groove cut in the pot of clay in the cup is then measured. This test is called the Atterberg test.

The plastic limit is defined as the limit below which the clay will stop to behave as a plastic and will start to crumble down. To measure such a limit, a sample of the soil is formed into a tubular shape with a diameter of 3.2 mm (0.125 in.), and the water content is measured when the cylinder ceases to roll and becomes friable.

The difference between the liquid and plastic limits is defined as the plasticity index

$$P_I = L_L - P_L$$

Clays with a diameter smaller than 2 μm contribute to the high plasticity index.

Plasticity index signifies the range of moisture content in which the clay keeps its integrity as a plastic lump.

In their natural status, dredged materials contain water content ω_n equal or greater than the plastic limit.

A map of the properties of the deposited sediments in Lake Nasser is not available in the open literature. It is therefore important to review the plasticity index of sediments of the Nile floodplains, all the way to Palestine [11].

Although there is a tendency to believe that the sediments of the Nile were entirely the gift of the Nile since Herodotus expressed his famous opinion “Egypt is the gift of the Nile", Said [1] points out that the Egyptian old delta north of Cairo is the result of a much older geological pattern and therefore that the Nile contributed marginally to its formation. In fact, he would argue that most silt transported during the flood zone ended up in the Mediterranean sea and drifted to Palestine (Israel since 1948), Lebanon, and Syria. It is therefore difficult to draw a direct relationship between existing sedimentology of Egypt and current movement of clays through the Aswan High Dam Reservoir. Observations on clays in the top layers for the last few thousand years may yield an indication of the challenges for new community development through dredging. Observations at depth in excess of 5 meters appear to be irrelevant to the current problem.

Woodward et al. [12] summarized the distribution of clays and silts along the Nile starting from Khartoum, Sudan, as follows:

- Smectite-rich sediments (>60%) being brought with the Blue Nile from Ethiopia
- Smectite-rich dominated assemblage (50–80%) forming in the new delta at Lake Nubia, mixed with lacustrine deposition post-1964 with material being transported from Red Sea Hills transported by local winds
- Lake Nasser with a kaolinite-rich assemblage (>50%) in bottom and suspended loads in central and northern Nasser lake (and to 70%) transported northward to Qena, in combination with lake margin erosion due to wind blowing from north and west (northwesterly)
- Erosion along the Nile north of Qena of pre-1964 smectite assemblage
- Smectite-enhanced (60–70%) assemblage similar to pre-1964 conditions between Qena and Cairo
- Smectite-rich assemblage (>70%) in the delta north of Cairo

Woodward et al. [12] estimate that clay size material (<2 μm) is the major element that moves north through Lake Nasser, as most silt and fine sand deposit in Lake Nubia. Based on the fieldwork of Stanley and Wingerath [13, 14], the clays moving north through Lake Nasser consist of:

- 70% smectite
- <25% kaolinite
- <10% illite

These clays are of volcanic origin from the sources of the Nile. However, as the Nile water moves north into Egypt, they pick up kaolinite blown into the AHD Reservoir by the wind from the desert from erosion of the shores of Lake Nasser.

Concentrations of clays containing 30% kaolinite have been recorded to move at the rate of 10 km/year and have been observed at Qena, some 350 km north of the AHD. Stanley and Wingerath [13] therefore predicted that these clays would gradually reach Cairo and continue to move north into the Mediterranean shore by the end of the twenty-first century. This northerly movement of kaolinite is insufficient to compensate for the erosion of the coastal plain due to the entrapment of most sediments in Lake Nubia and Lake Nasser.

Labib and Nashed [15] investigated the clays of the Toshka region and along Sheikh Zayed Canal. They also commented that expansive clay existed throughout Egypt. They collected 49 samples. Some important parameters for dredging were:

- Particle size smaller than 0.002 mm (clay fraction) ranging from 18.51 to 85.81%
- Liquid limit $44.70\% \leq L_L \leq 104.50\%$
- Plasticity Index $24.30\% \leq \mathrm{PI} \leq 82.98\%$
- Activity PI%/clay fraction% 18.51–85.81
- Density of sediments $2{,}580\ \mathrm{kg/m^3} \leq \rho_s \leq 2{,}650\ \mathrm{kg/m^3}$

El-Ghafour et al. [16] discussed the suitability of the Toshka clays for the manufacture of ceramic products and recommended slow firing as the clays are plastic and have sensitive properties upon drying.

Yassien et al. [17] sampled the soils of Qena. The main elements of the clays consisted of ferric oxide (Fe_2O_3) at 19.20% and aluminum oxide (Al_2O_3) at 12.85%. The sediments of El Salheya clays consisted of a mixture of quartz, montmorillonite, and allite as major components and kaolinite, illite, and calcite as minor elements. Clays were 14.3–16%:

- Liquid limit $41.00\% \leq L_L \leq 44.80\%$
- Plasticity limit $26.50\% \leq L_L \leq 28\%$
- Plasticity index $17.80\% \leq \mathrm{PI} \leq 20\%$

El-Shinawi and Naymushina conducted tests on the floodplains in southeast Aswan City and found that soils up to a depth of 4 m consisted of clayey sand (SC), but at a depth of 9 m and lower, there were mostly well-graded sand. Fines in the top 4 m layers, therefore, consisted of 13% fines, 81.4% sand, and 5.2% gravel. The density of sediments ranged from 2,520 to 2,710 kg/m^3. Bulk density was however as low as 1,100–1,700 kg/m^3, thus confirming a high void ratio. Plasticity index values were not reported, but from other sources in the literature, these soils are not expected to yield high plasticity index.

Bayoumi and Ismael [18] examined the distribution of clays in Egypt. The authors estimated that there are large reserves for ball clays mainly northeast of Aswan City. Samples were taken at two sites:

- Wadi Abu Subeira – with clays finer than 2 μm diameter representing 45–58% of the sediments (12 km north of Aswan)
- Wadi Abu Agag – with clays finer than 2 μm diameter representing 47–58% of the sediments – location $24^{\mathrm{o}}00$ N, $33'03^{\mathrm{o}}$ N

Kaolinite was the main component for the clays at 39–60%, with illite at 10–19%. Quartz was at 25–46% depending on the sample. Values for plasticity index were not tabulated as the authors focus on the geochemistry and concluded that ball clays from Northeast Aswan are good candidates for the manufacture of ceramic industrial products.

El-shinawi and Naymushina [19] tested the geotechnical properties of southeast Aswan flood deposits. Soils were formed of friable clays, clayey sand, calcareous material, sand and gravel.

Kharbish and Farhat [20] reported that Wadi Badaa in the Cairo-Suez district of Egypt had sediments with clays mainly composed of smectite and kaolinite. The plasticity index was in the range of 24–30%. Particles with a diameter smaller than 2 μm constituted ~33% of the sediments.

Abu Seif [21] discussed the contamination of soils in Upper Egypt from leaking wastewater systems. He estimated that the average thickness of clayey layers in the floodplains of Egypt between Aswan and Cairo was 10 m. The sediments for Upper Egypt were examined between the latitudes (32°20 E, 32°15 E) and the longitudes (26°10 N and 26°45 N). The amount of clays with mean diameter <2 μm determine their ability to swell in contact with water. Samples exhibited a high void ratio as the dry density varied between 1,833 and 1,993 kg/m^3. Soils contaminated with wastewater varied between 1,795 and 1,965 kg/m^3. Samples treated with tap water exhibited a plasticity index of 18–40%, while samples treated with wastewater had a plasticity index in the range of 35–53%.

Abu Seif and El-Shater [3] collected samples in Sohag. Recent deposits contained 15–26% clay, 40–54% silt with the balance being sand. Plasticity index for recent deposits was in the range of 17–23%.

Kalabsha is located 50 km south of Aswan. Bayoumi and Gilg [22] examined the sediments of Kalabsha. The sediments contained nodular, pisolitic, and plastic kaolins. These clays were rich in niobium, an important mineral for the modern electronic industry. Laterite was also found.

Ezzat et al. [23] collected samples for sediments at Khor El-Ramla, Khor Kalabsha, and Khor Wadi-Ayad Allaqi of Lake Nasser. The clay fraction was composed of mainly kaolinite and smectite with illite as traceable amounts.

3 Hydraulic Dredging for Community Development

In July 2004, the Minister Abu Zeid announced that a pilot project would be started at Abu Simbel with a grant from Japan over 6,500 acres. Said [1] reported that the pilot project failed due to a number of reasons:

- Lands are difficult to reclaim due to poor desert conditions.
- Huge annual water fluctuations of the reservoir making irrigation difficult.
- Resistance to agriculture that could have an impact on the quality of water.
- The need to maintain an arid buffer zone at the border with Sudan to prevent the spread of diseases and pests from Equatorial Africa that could become endemic in Egypt, such as the Gambian mosquito that invaded Egypt in 1942.

Said [1] did not propose solutions to the failed pilot project at Abu Simbel but simply commented that it had been abandoned. There may have been other considerations, such as a drop of interest in infrastructure projects following the 2011 revolution when Egypt faced difficult economic challenges, lack of tourism, and an atmosphere not prone to investment.

During the construction of the Aswan High Dam, the government of President Nasser took the illogical decision to relocate villages from Nubia to Kom Ombo well north of Aswan. This ill-fated decision broke the traditional link between the Nubian villages and surrounding pastoral nomads. For thousands of years, the villagers shared their goats and sheep with pastoral nomads in the winter season when humidity allowed for limited vegetation in the desert. The animals were returned in the spring and divided between farmers and nomads. While UNESCO mobilized funds to move the ancient temples of Nubia, like Abu Simbel and Philae to higher grounds, populations were uprooted by the stroke of a pen.

Nasser died in 1970. In an irony of history, his successor President Sadat has a Nubian mother. President Sadat focused his energies and all resources of Egypt into recuperating the Sinai lost during the 1967 war. He did not live long enough to rectify the displacement of Nubians and was assassinated in 1981. His successor President Mubarak completed the last part of the High Dam Reservoir project, namely, the Toshka project. It was originally conceived as a safety valve, to divert floods when the Nile waters were too high and could endanger the High Dam, but was transformed to a gateway to the New Valley.

Following the 2011 Egyptian revolution, the new 2014 constitution recognized the right of Nubians to return to their ancestral lands [24]. The area west of the Aswan High Dam has now been designated as a military zone for megaprojects. Nubians are concerned that they may lose the right to return to their ancestral lands as megaprojects are planned. Most Egyptians would not bear the very harsh and arid conditions on the shores of Lake Nasser. It is most likely that the workers executing such projects will be Egyptian Nubians.

Megaprojects require very high investments which are not available in Egypt. Small community development could be a more effective tool for development.

The claim made by some authors such as Said [1] that the shores of the AHD Reservoir are too poor for farming should be disputed considering the potential hydraulic dredging of clays and applying them to the banks of the Nile.

Tests conducted by the US Corps of Engineers, reported by Mitchell [25], in the USA, confirm that the application of clays to dredged sands enhances root growth. In their tests, clays such as attapulgite, bentonite, kaolinite, and montmorillonite were applied at the rate of 9–57 short tons per acre. The results indicate that these clays enhance the growth of smooth brome grass even in a period of drought.

Abulnaga [10], Abulnaga and El-Sammany [2] and Abulnaga and Abdel-Fadil [6] have proposed to overcome the problem of poor desert soils, through dredging the sediments, and the construction of dedicated slurry pipelines and sediments ponds at safe areas. The technology can be applied equally for small and megaprojects at different scales.

As early as 1910, the clay worker [26] reported that many brickyards in Germany resorted to wet dredging of clays to manufacture bricks. This concept that existed 110 years ago could be implemented on the shores of the Aswan High Dam Reservoir to establish new artisanal plants for the manufacture of bricks. There are currently no similar projects of direct hydraulic dredging to brick manufacture although the technology is more than 100 years.

Table 1 Potential advantage and disadvantages of hydraulic dredging of high-plasticity clays from the AHD reservoir

Advantages	Disadvantages
High-plasticity clays delivered as balls on the discharge of the dredging pipe can be collected and sent fast to a manufacturer of bricks or ceramic products	Need the dredger to be constructed with a special cutter on the suction of the ladder pump
Balls of clay sediment can be pressed by a bulldozer into a dyke or to form further impermeable canals in the desert	Balls of clays tend to deposit in dredging pipelines if the flow velocity in the pipeline is too low
Smectite clays applied at an average rate of 25 tons/acre stabilizes the growth of grass in poor soils	Balls of clay cause a higher level of friction in the pipeline by forming a sliding bed at the bottom of the pipe and increase power consumption over low plasticity clays that can move as a slurry
Clays are available throughout Egypt at the AHD Reservoir, Toshka, and Upper Egypt up to Qena and moving north into Cairo	Not recommended to erect homes on the sediment of high-plasticity high clays, due to their tendency to swell in the presence of wastewater or floods

The Toshka projects have been often criticized as a failure due to the high nature of clay deposit according to Fecteau [27], who reported on the work of Emma Deputy at the University of Texas at Austin, USA. She claimed that the large autonomous irrigation machines often get stuck in bowls created by drying clays. Deputy also reported that the Egyptian government canceled the second phase of the project that was due for completion in 2017. Canal Zayed was supposed to reach the oasis Baris but is now 60 km short of the target.

There are also other claims that need to be subject to scientific scrutiny. One claim made is that the water of the Nile from Toshka mixes with the salinity of the soil in the desert and filtrate into fossil water causing contamination. This claim is in itself is in contradiction of the claim that Toshka is covered by clay. In reality, the high-plasticity clays of Toshka would swell in the presence of water and lock up to firm an impermeable barrier to water seepage.

Rather than considering Toshka a failure, it should be turned into a mine for the ceramic and brick manufacture. Table 1 summarizes the economic value and potential for creating numerous employment opportunities from the clays of the AHD Reservoir.

It is clear that clays of the Nile consist of two principal components kaolinite and smectite.

Kaolinite is often mined for numerous industrial applications such as:

- Ceramics (porcelain)
- Light diffusing material in incandescent light bulbs
- Cosmetics
- Paint ingredient to extend the titanium dioxide (TiO_2) white pigment and modify gloss levels

- Ingredient to modify the properties of rubber upon vulcanization
- For organic farming as a deterrent for insects
- In a number of medical applications such as treatment of diarrhea, toothpaste, suppressant for hunger
- Ingredient to accelerate the hydration of Portland cement
- Paper industry
- Ingredient for wastewater treatment

Many processes to extract kaolinite from deposits involve the formation of the slurry to transport it and process it. Since the process of dredging the Nile sediments already involves the formation of a slurry mixture with water from the Nile, it would be conceivable to install an inline plant to extract the kaolinite as an industrial product to recover the cost of dredging.

The initial step when mining dry china clay involves using chemical dispersants to suspend the clay particles. This step is called "blunging." The need to add dispersants at the end of the dredging pipeline would have to be confirmed through testing, but the information is not currently available in the case of the Nile sediments as the exercise has not been started.

The second step is called "de-gritting" – the slurry pipeline discharges through sieves into settling tanks. Sieves are normally 40 mesh, 100 mesh, and 200 mesh, and sand, mica, and other impurities are extracted. The settling tanks are designed with internal barriers to zigzag the slurry and enhance sedimentation of the clay. The concentration of the slurry increases gradually to 60% in the sedimentation ponds or tanks. As an alternate step to sedimentation tanks, powerful centrifuges are used to form a paste. The resultant paste is then passed through vacuum filters, and large gas fired spray dryers to remove and evaporate the remaining moisture.

In an Egyptian context, the last step could be modified to rely on solar energy for drying the kaolin. Modified greenhouses as those used for solar distillation permit to recuperate water evaporated in the process. A smectite is a group of phyllosilicates such as montmorillonite, beidellite, nontronite, saponite, and hectorite. Properties and industrial uses of smectite were reviewed by Odom [28].

Natural smectite clays can be divided into three principal groups:

- Sodium (Na) smectite
- Calcium-magnesium (Ca-Mg) smectite
- Fuller earth smectite

Natural sodium smectite occurs only in very few locations, while the other two types are much more common. Ca-Mg smectite is used in foundries, oil well drilling (as drilling mud), wine, iron ore extraction, feed pelletizing industries, and civil engineering to form permeable layers impeding the flow or seepage of water. Ca-Mg smectite is also used for filtering and for decolorizing various oils.

Fuller acid earths are used for decolorizing oils and fats, as absorbents for oils and grease, and as carriers for insecticides. According to Elba and Farghaly [29], the Egyptian government adopted decree 203/2002 which requires maintaining a buffer zone of 2 km around the lake to preserve the environment. Therefore, any effort to dredge the clays of the AHD Reservoir must be made over a distance of few kilometers.

Sediments can be diverted to fill existing wadis [30] with construction of small dams.

4 Past Efforts for Cutting and Dredging the Clays of the Nile

The first attempt to use modern hydraulic dredging on the Nile and to cut away its clays dates back to 1911 [31]. From 1882 to 1953, Great Britain administered Sudan in collaboration with Egypt. In May 1911, the International Marine Journal reported that the Egyptian Department of Water Works was advised by Mr. C.E. Dupuis and Mr. O.M Tottenham Inspector, General Irrigation, to build a special clay cutter and hydraulic dredging machine for cutting canals at Khartoum, Sudan. The dredger was manufactured by Lobnitz & Company Ltd. of Renfrew, Great Britain. It was shipped by boat and rail and then assembled in Khartoum. The International Marine Journal wrote in its May 1911 edition:

> The dredger is of the hydraulic type; it is designed to make wide cuts in the river and to deposit the spoils on the banks through a floating pipe line having a suspended shore discharge.

This interesting dredger/clay cutter consisted of a steel hull 49.4 m (162 ft) long × 11.6 m (38 ft) beam. It was propelled by a paddle wheel and operated by steam boilers powered by coal. The clay cutter made lateral cuts in a circular fashion swinging 45.7 m (150 ft) and cutting to a depth of 7.6 m (25 ft). The dredge pump was powered by a 700 hp triple expansion steam engine. The vessel featured as special rotating clay cutter. The vessel was one of the first to ever use all metal ball couplings between sections of the floating pipe.

This effort was the first historical effort to cut and dredge the clays of the Nile and transport them in dedicated slurry pipelines. The knowledge acquired at a time of colonialism was not transmitted to Egyptian and Sudanese engineers and was lost to history. Both Egypt and Sudan did not have national engineers and scientists in 1911.

Data on power consumption were not published from this first attempt.

5 Challenges of High-Plasticity Clays to Hydraulic Dredging

The mechanism of clay cutting in dredging [32, 33] ranges from shearing to high pressure jetting.

Although the high plasticity of clays is viewed as a problem for construction of new buildings in their floodplains, it is advantageous for construction of new ponds and for ceramic and brick manufacture.

The basal properties and composition of clays greatly influence their cation exchange capacity, plasticity, and ability to swell. Verbeek [34] (Quoted by Leschinsky et al. [35]), Sorensen [36] (Quoted by Leschinsky et al. [35]), and Eskin et al. [37] commented on the importance of soil properties and the difficulty of pumping clays. This was also confirmed by Verhoeven et al. [38].

Wilson et al. [39] presented a case for pumping dredged balls of clay and showed an important increase of friction losses in the dredging pipeline.

The research conducted by the US Corps of Engineers shows that for very dense material, the degradation of formed clay balls is negligible for any plasticity index greater than 25%. These tests were limited to the tangential velocity of 2.3 m/s in rotating drums. The tangential velocity is not exactly the velocity of movement of the lump. As it degrades, its center of mass shifts closer to the wall of the drum, and there is a small difference between starting and final conditions.

Artificially prepared samples by the US Army Corps of Engineers

- Soft clay (PI 25 – degradation up to 40% and PI 54 degradation at 18%) at (2.5 m/s or 8.2 ft/s)
- Medium clay (PI 25 – degradation up to 12% and PI 54 degradation at 5%) at (2.5 m/s or 8.2 ft/s)
- Stiff clay (PI 25 – degradation up to 3.8% and PI 54 degradation at 3.5%) at (2.5 m/s or 8.2 ft/s)

Based on the recommendations of the USACE, as well as the technical note prepared by Leschinsky et al. [35] for the American Society for Testing and Materials, the ASTM did not believe that there was sufficient data to transform the note into a standard.

According to the note, the following criteria should be used to determine the potential for formation of balls of clay during hydraulic dredging:

- Plasticity index >25%
- Shear strength >25 kPa (0.52 kips/ft^2)

It is important to emphasize that Leschinsky et al. [35] stated that these parameters are indicative and not absolute and needed to be confirmed in the field. They wrote:

> If the relationships obtained in this study are shown to be valid in the field, this information will be useful in selecting dredging equipment, designing dredged material containment area, and estimating costs. Relatively undisturbed specimens of the in situ clay and simple laboratory tests would provide the necessary information.
>
> The purpose of this reported study was to empirically quantify the relationships between basic clay properties and the degradation rate of clay lumps in an environment that simulates hydraulic transport conditions. Using the empirical relationships established in this study with the equivalent soil properties at a particular dredging site and the anticipated flow velocity and time in the dredge pipeline, predictions regarding lumps degradation, selection of dredging equipment, and cost estimate can be rationally made. However, since this study was carried out in a simulated environment using synthesized clay, a field verification of its predictions is necessary. Consequently, this paper is published as a technical note.

6 Ablation Tests

Since the ASTM note recommended laboratory tests on natural clays rather than artificial clays as prepared by the US Army Corps of Engineer, it was decided to conduct ablation tests on natural clays. Samples were not available from Egypt, so samples were dredged from a location in the USA known for high-plasticity clays.

Many dredging projects operate at a velocity higher than 8.2 ft/s (or 2.5 m/s), and it is, therefore, difficult to extrapolate the data from the controlled tests of the USACE to field conditions.

Figure 2 shows an example of balls of clays from a site in Texas, USA. The units are in feet (1f = 1 foot = 304 mm) on the upper divisions and in inches (25.4 mm) in lower scale. Balls of clays still existed after passing through the dredging pipeline and five pumps in series and after pumping through 7–8 km. Balls had a diameter of 100–150 mm. These balls of clays can be pressed in place to form new topsoil layers by a bulldozer, faster than a standard sedimentation process for low plasticity clays. In fact, low plasticity clays may not deposit until all the water in the pond evaporate.

To understand the problem of high-plasticity natural clays, samples were obtained from a dredging contractor (Fig. 3). The sample had a plasticity index of 32% (see Table 2).

Fig. 2 Ball of clays formed during dredging high-plasticity clays in Texas. Scale is in feet (1F = 304 mm) and inches (25.4 mm)

Fig. 3 Cutter and collected samples of clay from hydraulic dredging barge in Texas (USA)

Table 2 Clay sample collected in Texas for ablation tests

Sample	Moisture content	Specific gravity	Liquid limit	Plastic limit	Plasticity index
Texas clay	25%	2.49	49%	17%	32%

An ablation machine was built at the slurry lab of Splitvane Engineers Inc. (see Figs. 4, 5, and 6), and the Splitvane ablation or attrition wheel, therefore, consists of a cantilever bearing assembly with an 80 mm diameter shaft that extends 1,000 mm into a water basin.

At the end of the shaft, a rotor was installed. The rotor had a diameter of 450 mm OD, 425 mm ID. An internal weld bead was left in place to represent the HDPE weld beads that are found in pipelines at 12–15 m intervals.

To operate the machine at very low speed, the ablation machine was connected to a Computer Numerical Control center – from Siemens with a Direct Current Motor.

Many samples were compacted in a 100 mm die using a press (see Fig. 7). Tests were run as a function of velocity in the pipeline for a duration representing pumping over a distance of 8 km. Diameter and weight were measured at regular intervals for each tangential velocity of the drum.

Figure 8 summarizes results of ablation tests in terms of tangential velocity of the drum and pumped distance as the ratio of final to original mass.

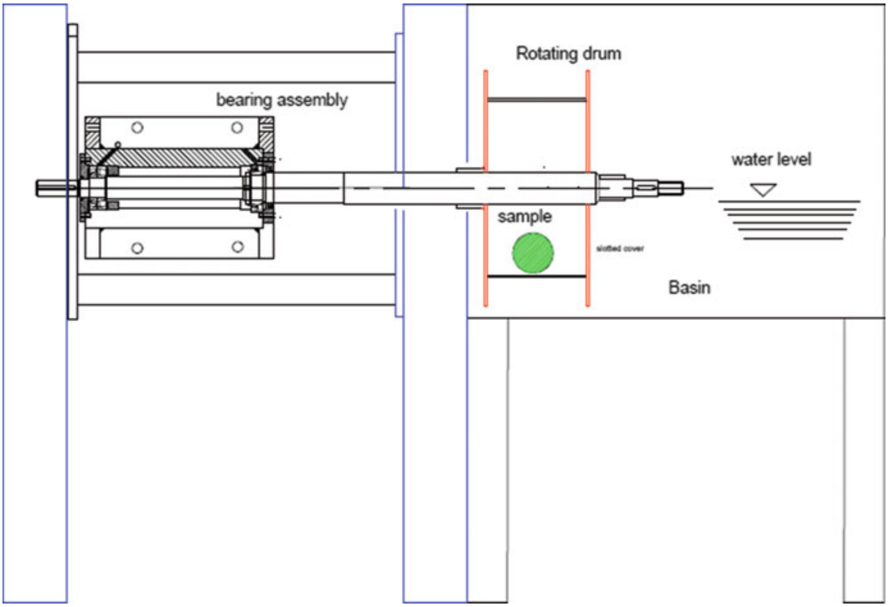

Fig. 4 Ablation machine with rotating drum built by Splitvane Engineers

Fig. 5 Construction ablation machine connected to Siemens computer numerical control drive

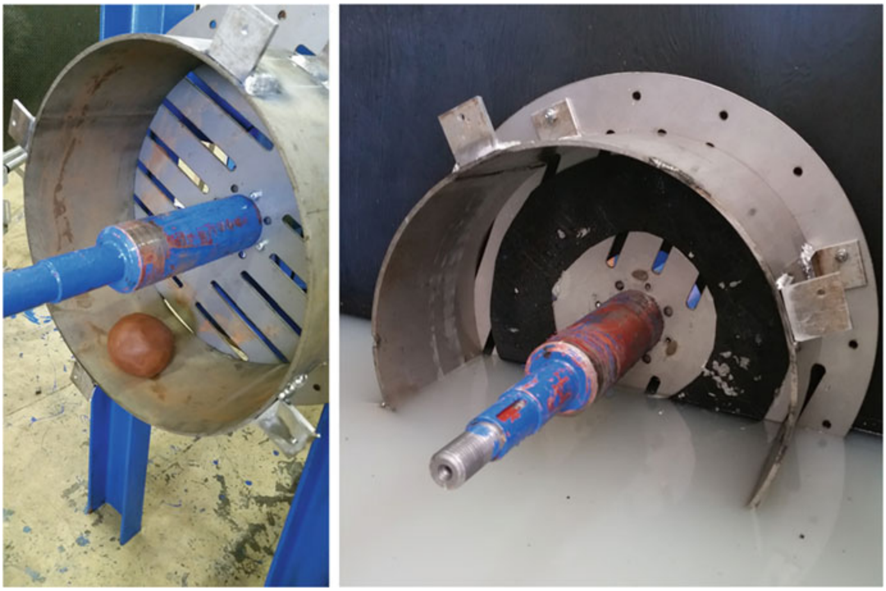

Fig. 6 Drum and side screens – in order to avoid cutting off the edges of the ball by the slots, an internal lining was added; the drum is filled to shaft level to ensure immersion of the clay sample

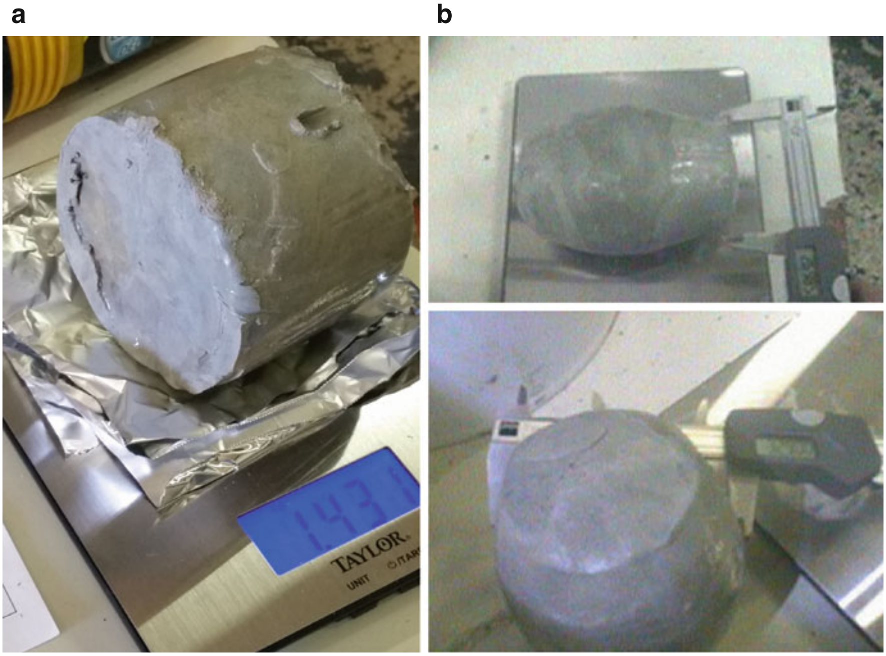

Fig. 7 Sample before and after ablation at 4.9 m/s. (**a**) Original sample A. (**b**) Sample ablated after testing at 4.9 m/s for a period corresponding to pumping over 7,600 m

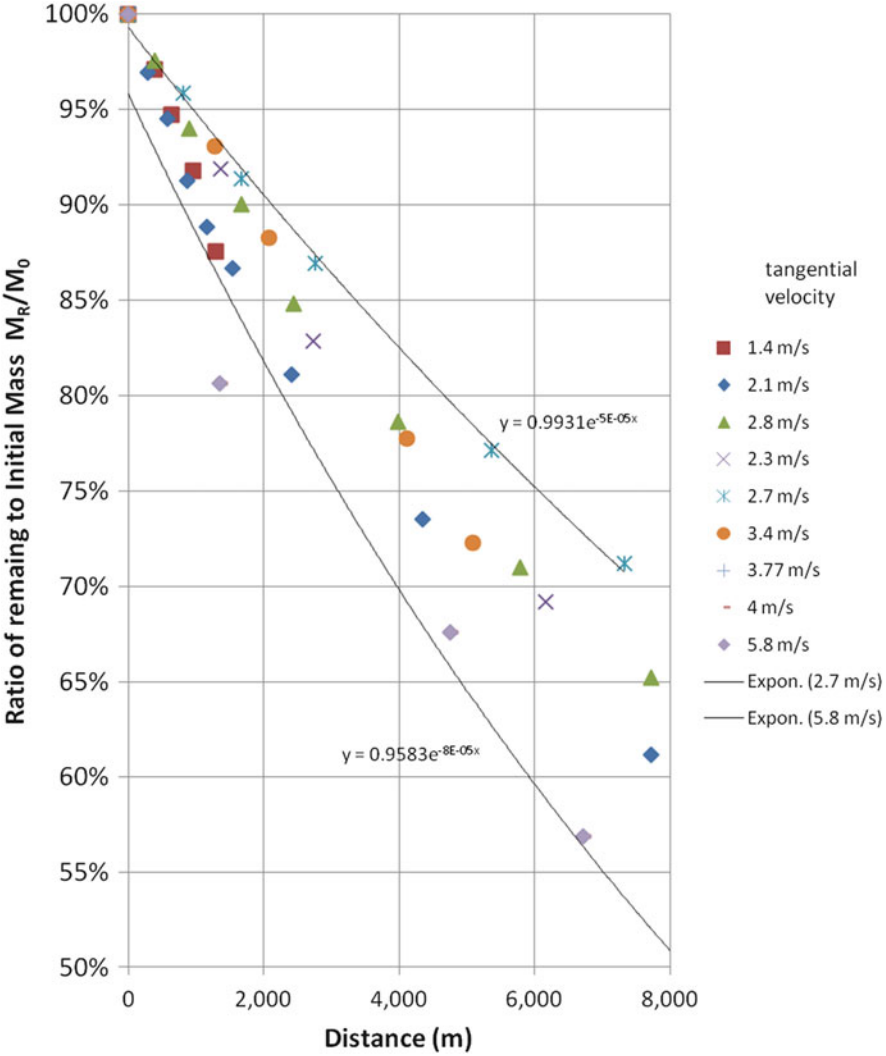

Fig. 8 Ablation of clay with plasticity index of 32%, for sample dredged in Texas

7 Discussion

Figure 9 presents a flow chart for the flow of sediments and accumulation or removal of clay deposits in Egypt and Sudan. The new delta is shown as capturing most sediment offering an opportunity for new communities' development through dredging. The Nile Valley Egypt is shown to be a continuous site for accumulation and erosion of clay sediments. This situation is different from the traditional sites

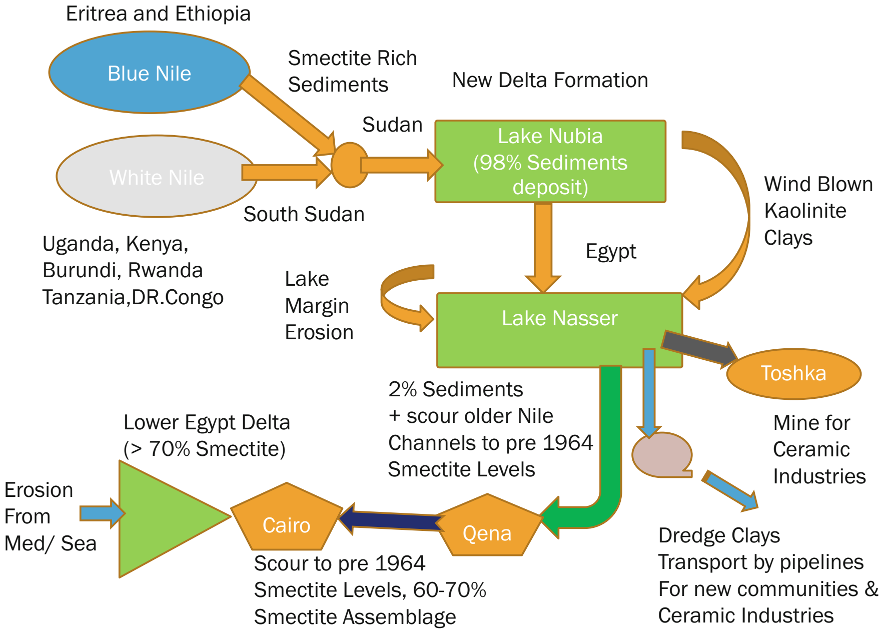

Fig. 9 Flow chart for the flow of sediments and accumulation or removal of clay deposits in Egypt and Sudan. Areas marked in red identify potential extraction by dredging to build new communities and develop ceramic industries

for dredging such as the Suez Canal and must be differentiated by the plasticity index of clays of the Nile.

The published papers such as in 1994 by the US Army Corps of Engineers [40] and by Leschinsky et al. [35] emphasize the problem of slow degradation of high-plasticity clay. In the ideal world of dredging the clays would ablate very fast and transform themselves into slurry. The fundamental concern of these simulated tests is that they fail to develop a correlation with time or pumped distance; in some respect the American Society for Testing and Materials was correct to refrain from adapting the technical note into a standard.

Tests conducted at the slurry lab of Splitvane Engineers on dredged clay at a plasticity index of 32% will retain 80% of their mass as lumps and lose 20% as slurry within the first 3 km at pumped velocity smaller than 3.5 m/s, but degradation will accentuate at a higher velocity. Despite the higher cost for pumping balls and lumps of clay, there are numerous advantages for them to retain as much as possible their original mass. Delivered as balls, they can be used for ceramic brick manufacture or pressed in place as topsoil for farming while draining away excessive water.

The pumping velocity depends on many parameters such as the diameter of the pipeline, the volume concentration of clay in the transported slurry, the specific gravity of particles, and rheology. It is not uncommon to operate at 4–5 m/s in

600–700 mm nominal bore pipes. Lower velocities are associated with smaller diameters, and this may be the case for small community development.

Even if the dredging boat was close to shore, the pipeline would have to cross the so-called environmental buffer zone of 2 km before reaching a center for industrial or farming activity. The further the dredging boat move into the reservoir, the more degradation is expected. It will be necessary to ask the Egyptian government to modify the decree banning any activity within 2 km of the shore to allow the collection of balls of clay with minimal degradation.

- The decay is exponential and follows the following equation:

$$\frac{M_r}{M_0} = Fe^{-Bx}$$

where M_r is the remaining mass of lump, M_0 initial mass of lump, F factor that depends on velocity and properties of the lump, B exponent that depends on velocity and properties of the lump, and X pumped distance in meters from dredger to final delivery.

These results are therefore different than those presented in 1994 by the US Army Corps of Engineers [40] and by Leschinsky et al. [35] who presented time-independent data. The data collected by Splitvane Engineers on real dredged material showed that ablation depends on pumping distance, the presence of shells, fine sand, and organic material.

For a plasticity index of 32%, the tests of USACE predicted:

- Soft clay (density = 80% maximum value), 25% loss of mass to degradation at 2.3 m/s tangential velocity
- Medium clay (density = 90% maximum value), 7% loss of mass to degradation at 2.3 m/s tangential velocity
- Stiff clay (density = 100% maximum value), 3.5% loss of mass to degradation at 2.3 m/s tangential velocity

To some extent, the increase in degradation with natural samples would reduce friction losses in the pipeline by creating a carrier fluid with fines. These fines will, however, take a longer time to deposit once delivered but could be used for farming by diverting them to settling ponds.

As shown in (Fig. 10), Lab tests on real dredged clays show a faster degradation than artifical samples tested by the USACE.

Further tests should be conducted in Egypt on samples from the AHD Reservoir and north in Upper Egypt up to Qena as 2% of the sediments manage to pass through the turbines of the dam. The shear strength and plasticity index should be measured on test samples.

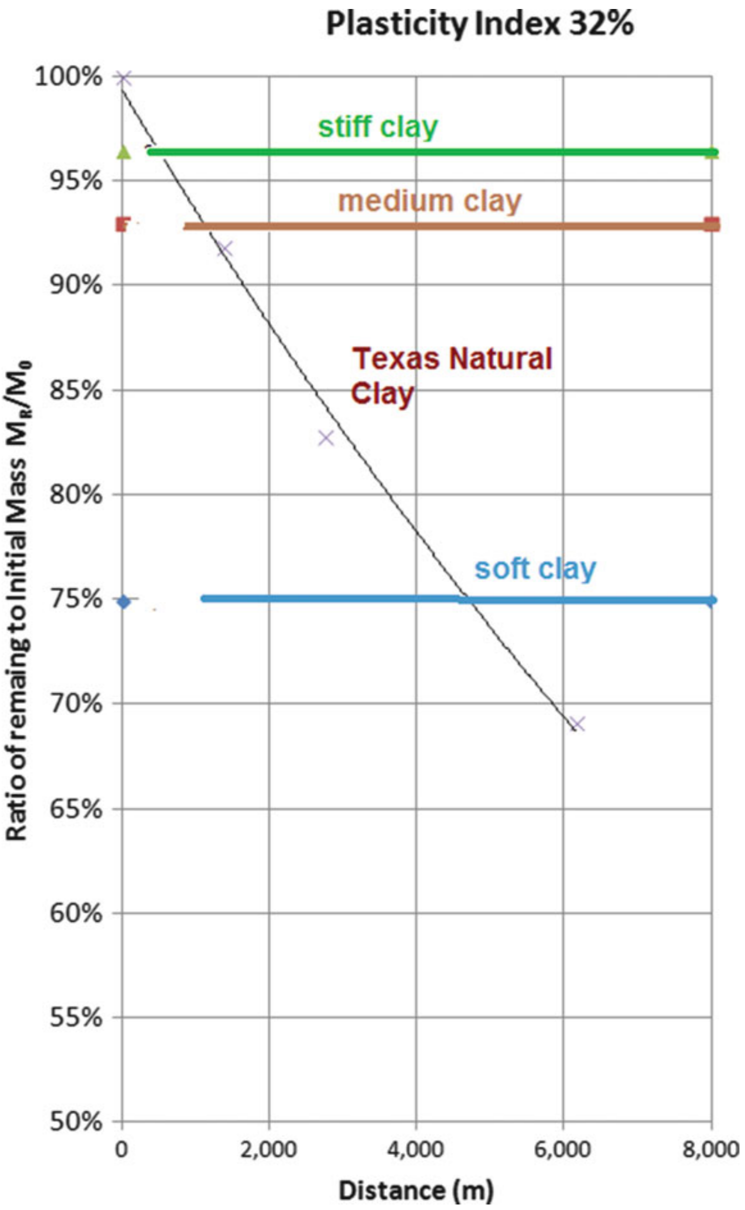

Fig. 10 Comparison between ablation of a natural sample from Texas and a synthetic sample prepared by the USACE - Texas clays exhibit faster ablation

8 Conclusion

The majority of coarse sediments will continue to deposit in Ethiopia and Sudan even before reaching Egypt. The construction of the GERD is likely to accentuate the separation of coarse and fine sediments. However, due to their content of very small particles, clays and some fine silt will continue to pass through.

Data collected over the last 50 years indicate that 2% of the sediments tend to reach Qena after passing through the High Dam. The clays deposited in the AHD Reservoir are mainly composed of smectite (~70%) of volcanic origin. Kaolinite is blown by wind or deposited from erosion of the banks of the reservoir (~20%).

The deposited clays tend to have a high plasticity index. They represent a challenge for dredging. If traditional dredging equipment is used, these clays will tend to form balls in the slurry pipeline and increase friction losses. Tests on similar natural dredged clays of plasticity index of 32% will retain 80% of their mass as lumps and lose 20% as slurry within the first 3 km at pumped velocity smaller than 3.5 m/s, but degradation will accentuate at a higher velocity.

The study recommends:

- Special dredging platforms with clay cutting and pulverization equipment
- Calculating in advance the high friction losses associated with moving balls of clay in dredging pipelines

Despite these challenges, Nile clays can form the basis of a strong ceramic industry and for topsoil in desert reclamation projects. Certain failures in the Toshka project are indicative of a misunderstanding of the nature of the expanding clays. Proper engineering solutions are needed require training of technicians and engineers.

9 Recommendations

The construction of the GERD will accentuate the capture of the coarser silts and sands that would have reached Lake Nubia in Sudan and Lake Nasser in Egypt. However, clays are too small to be captured and will continue to filter through the various reservoirs in Ethiopia and Sudan.

Nile clays are mainly composed of smectite and kaolinite. They present certain engineering challenges, as dredging, farming, and construction material.

Clay science is becoming a special branch of civil, chemical, and dredging engineering. There are a number of international magazines, such as *Applied Clay Science*, *Handbook of Clay Science*, etc., that reflect 50 years of research on a worldwide scale. Egyptian experts for clay science are very few and scattered.

It is recommended that a symposium be organized inviting the experts to discuss the specific challenges of clays of the Nile and emphasizing how to develop an economy around their extraction.

It is also recommended that Egypt develop an Institute for Science of Clays with the following roles:

- Gather data on clays of the Nile.
- Develop proper methods for dredging clays.
- Design special clay cutting barges.
- Develop methods for pumping and hydrotransport of smectite and kaolinite of high plasticity index.
- Develop special low pressure bearing equipment for farming in difficult regions such as Toshka.
- Develop techniques for using clays as impermeable layers to retain water in reclaimed lands.
- Foster the industrial and medical uses of clays dredged from the Nile.
- Improve efforts to reclaim areas near Abu Simbel on the basis of clay science using dedicated specialists.

Collaboration with scientists, engineers, and decision-makers from Sudan must be emphasized since Lake Nubia is slowly changing into a new delta.

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Community Development by De-silting the Aswan High Dam Reservoir

Baha E. Abulnaga

Contents

Abstract Siltation of man-made reservoirs on the Nile is a very ancient problem dating back to Lake Moeris built more than 4,000 years ago in the Fayum area, in Middle Egypt. While this engineering work functioned trouble-free for 1,500 years until the Ptolemeans closed down some of the canals to dry out the shores and convert them to farmlands, modern problems following the construction of new reservoirs in the twentieth and twenty-first century suffer from rapid deterioration on a large scale. It is estimated that the Blue Nile transports 207 million cubic meters of sediments a year on the average, but most will now be retained by the GERD.

De-silting the large reservoirs of the Nile such as the Roseires, Sennar, Girba, and the Aswan High Dam, and in the future the GERD, should be done at the national and international levels through government- and private sector-sponsored programs. These programs can also offset the loss of reservoir capacity, increased evaporation losses due to the reduction of the surface to volume ratio, accumulation of weeds, and loss of hydroelectric power production due to sedimentation.

A careful analysis of the sediments in Lake Nasser with a preponderance of plastic clays reveals a sensitivity to potential dredging. The plasticity indices satisfy the conditions for the formation of balls of clays that would slow down dredging. It is therefore critical for Egyptian engineers to develop the technology for pulverizing the

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plastic clays when cutting them. Egypt can also become a platform for the development of technologies for de-silting the various reservoirs in Sudan and for training Sudanese engineers. Ultimately these efforts can lead to the development of small communities. The construction of a fleet of 80 dredgers with a minimum number of 240 booster pump stations and slurry pipelines averaging 5 km from the reservoir to the shores would be needed to dredge 100 million cubic meters each year and gradually restore the storage capacity of the various reservoirs. This effort would emulate the COAST 2050 project carried out in the USA in 2000 and the 2010s at more than US$15 billion.

Keywords Amenemhat, COAST 2050, Community development, De-silting, Dredging, Fayum, GERD, High plasticity clay, Iron ore, Lake Moeris, Lake Nasser, Lake Nubia, Roseires, Topsoil

1 Introduction

The first large reservoir for water was built in Egypt more than 4,000 years ago in Fayum [1, 2]. It could store 50 billion cubic meters of water [3] and protected Egypt from hunger for 1,500 years [1] but slowly silted and shrunk to a small size called today Birket Qarun. Siltation is not an exclusively modern problem but has increased sharply in the last 60 years, particularly due to deforestation on the Ethiopian heights [4]. It is estimated that more than 6 billion cubic meters of sediments have been deposited in Sudan and Egypt since the mid-1960s. Some reservoirs like Sennar and Roseires have lost more than 70% of their dead storage capacity by siltation. Lake Nubia is gradually becoming a new delta. Egypt in the process lost rich alluvium soils that used to be deposited with the yearly flood. The construction of the GERD is likely to stop most of the flow of the nutrient-rich sediments as it is designed to catch 207 million cubic meters of sediments each year [5].

A number of authors [6–16] have recommended dredging sediments from bottom reservoirs to enrich poor soils. The levels of trace elements and heavy metals must be assessed in the grown crops to comply with standards for food.

The clays of the AHDR are Smectite based with Kaolinite as a secondary component [17]. Past experience with this type of clays with a high plasticity index [18] indicates that cutting leads to stiff balls. The clay balls increase friction losses in the dredging pipelines [6, 18, 19]. A hydraulic analysis is presented to investigate the requirements for dredging large quantities for the establishment of new villages and communities with a set goal of dredging 100 million cubic meters per year or as the average rate of sedimentation has been around 140 million cubic meters per year since 1965 [8–10].

The effort would emulate on a larger scale the COAST 2050 [20–23] project in the USA, an effort to rebuild the shore of Louisiana in the USA through dredging and cultivation and estimated to cost $15 billion dollars, but could be brought down to an appropriate cost through the development of national industries.

2 Lake Amenemhat (Moeris), a 4,000-Year-Old Tale of Reservoir and Siltation

The irregular floods of the Nile have represented a challenge to local populations from most ancient times. Egypt being the gift of the Nile tried to master its waters.

The oldest dam in history called the Sadd El-Kafara (the Dam of the Pagans in Arabic) is believed to have been built around 2600–2700 BCE (before common era) some 40 km south of Cairo, Egypt, or 10 km south of Helwan [24]. The dam was constructed to protect Wadi Garawi and the Nile Valley. It was designed to store 465,000 m^3 of water. It was a rock-fill dam. The dam was designed to have a crest of 125 m but failed before completion according to Kumar et al. [25] due to soil stability problems. Sadd El-Kafara was built by King Menes, the first king of Unified Egypt according to Herodotus, but may have been built concurrently with the Great Pyramid of King Khufu (2900–2877 BC) according to Jansen [2].

According to Jansen [2], the dam had a crest length of 107 m. Its height was 11 m. “The faces were formed by rubble-masonry walls, each 24 m (78 feet) thick at the base and extending to the top of the dam. The total volume of these two rock walls was about 22,900 cubic meters (30,000 cubic yards). At the base, the walls are separated by a distance of 36 m (118 feet). Evidently the dam did not have the benefit of a cutoff trench excavated in the foundation. The core was filled with approximately 54,400 metric tons (60,000 tons) of gravel and other stones and probably some earth. The exposed face of the upstream wall was lined with stepped rows of roughly cut limestone blocks, evidently set with unmortared joints. The stones, reportedly having an average weight of approximately 23 kg (50 pounds), were placed in steps about 0.3 m (1 foot) high on a slope of 3 vertical on 4 horizontal. The massive section had a thickness from face to face of 84 m (274 feet) at the base and nearly 61 m (200 feet) at the crest. There is evidence that the top of the dam sloped longitudinally toward the center, causing the overflow to be concentrated at that point.”

The reservoir had a capacity of 570,000 m^3. Jansen [2] estimated that the collapse of the dam was due to the absence of a spillway.

Few centuries would pass before the Ancient Egyptians would attempt a gigantic project to master the waters of the Nile. Pharaoh Senusret III ruled over Egypt from 1878 to 1839 BC. Turning his attention to the Fayum Depression (Fig. 1), which was much lower than the nearby Nile River, he devoted the resources of Egypt toward digging a new canal that his son Pharaoh Amenemhat III and probably grandson Amenemhat IV were to complete. The Fayum Depression had previously been a swamp depression with localized lakes lower than the Nile River.

There is also evidence that the canal was started during the reign of the sixth dynasty around 2300 BC [26]. It was a time of drastic change of precipitations at the source of the Nile followed by low floods. During the twenty-second century BC, North Africa and the Middle East suffered from climatic upheaval. This event is called the 4.2 kiloyear event. It caused low floods, famine in Egypt, and the collapse of the Ancient Empire.

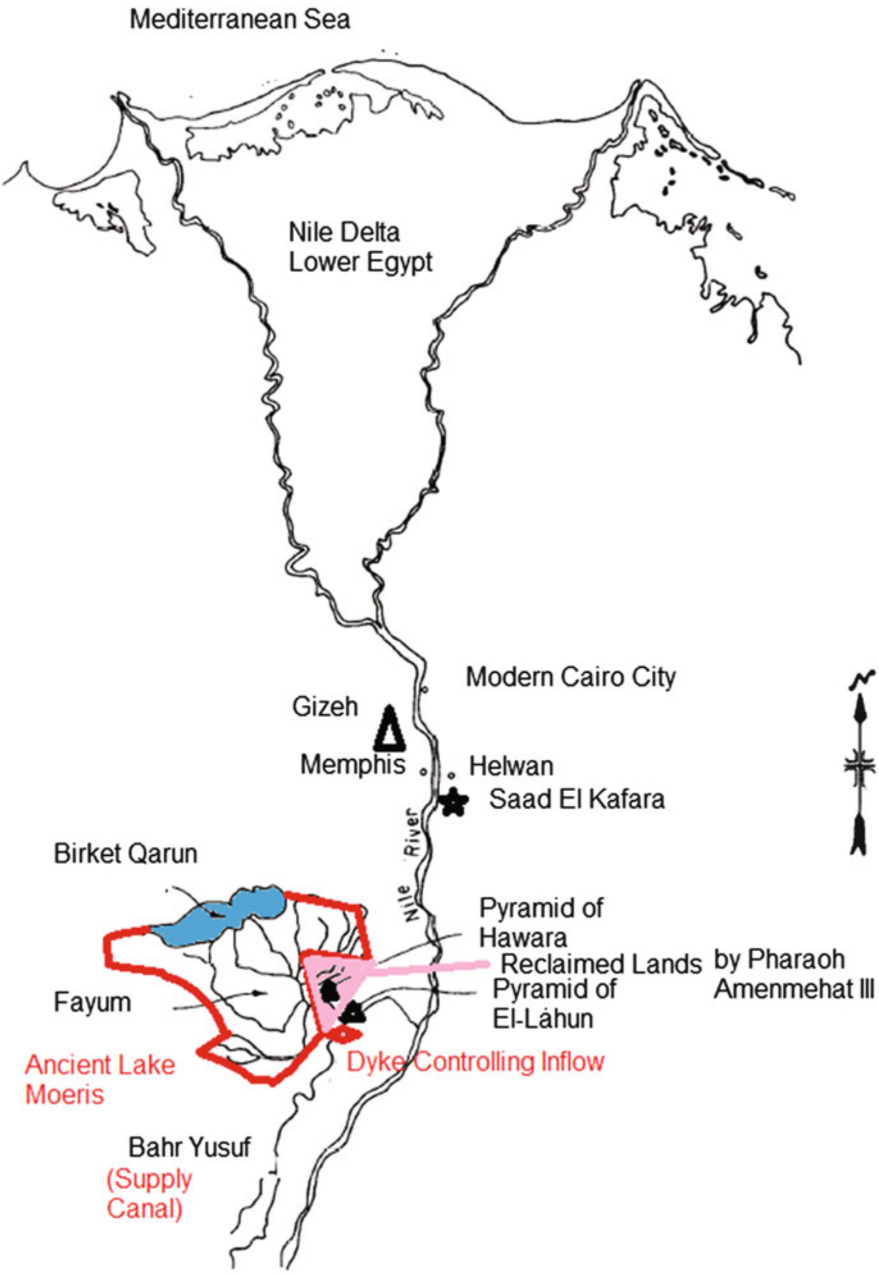

Fig. 1 Ancient Lake Moeris and Modern Birket Qarun at the Fayum Depression land east of Lake Moeris were reclaimed to build the city of Crocodilopolis

Arkell [27] analyzed the sediments and archeology and suggested that the Fayum area may have contained initially four separate lakes called Paleomoeris, Premoeris, Protomoeris, and Moeris. From excavations he suggested that the four lakes appeared and disappeared and rejoined into one lake according to the floods as follows: Lake Paleomoeris would have occupied the depression around 7000 BCE (before common era) reaching 11 m above sea level (ASL), while Lake Protomoeris reached 19 m ASL around 5200 BCE. The sediment analysis reported as discussed by Arkell [27] indicates that the level of the lake fell to 13 m amsl around 4000 BCE. Lake Moeris raised to 22–24 m amsl during the times of the Ancient Empire.

By digging a 16-km-long canal, the swamp was converted into a massive storage reservoir. The Ancient Egyptians called it the Great Canal “Mer Wer” but was renamed by the Arab conquerors few thousand years later Bahr Yussef. The Great Lake formed by this man-made reservoir was called the Great Lake by the Ancient Egyptians. The Greeks called Pharaoh Amenemhat, Moeris, and his lake became known as Lake Moeris. This is most likely a Greek corruption of Lake Amenemhat, as modern Egyptians tend to call the Aswan High Dam reservoir today Lake Nasser, after their ruler who initiated its construction. History tends to repeat itself on the Ancient Land of Egypt.

Two dams running east-west, called the Ha-Uar dams, controlled the flow of water. One of these two dams was a barrier at Wadi Gezzaweh, a ravine about 73 m wide at the base and was 11 m high [2].

The lake covered an area of 1,270–1,700 km^2. By comparison with the AHDR at 6,000 km^2, the Lake Moeris built 4,000 years ago remains an extraordinary fate of engineering. All that is left of it today is Birket Qarun covering 202 km^2.

The Ha-Uar dam is now called Hawara. According to Jansen [2], the Egyptians built two main regulators as earth dams 10 km apart. These two dams at Hawara Egland and Hawara El Makta diverted a large part of the Nile’s flow. Closing the gap between the river and the lake was done at the regulators.

The Ancient Egyptians dug two canals to the North and two canals to the south of Lake Moeris.

According to Hubert Chanson [3], a leading scholar on open-channel flows and Egyptian engineer, first attempts to connect the Fayum Depression with the Nile may have started much earlier than the twelfth dynasty of Amenemhat III. In fact, Chanson [3] dates some of the earliest attempts to 2900 BC and discusses the ability of Lake Moeris to absorb the flood, starting from 10 million cubic meters per day in June and climbing to a peak flow of 700 million cubic meters per day or 8.2 ML/s (million liters per second) in early September during the peak flood season. On the other hand, Jansen [2] estimated that the canal was 13 km long, 40 m wide, and 9 m deep.

Despite disagreements between experts, Jansen [2] estimated that the depth of Lake Moeris could have been 91 m deep. Reinterpreting the investigation of Willcoks [28], Jansen [2] concluded that Lake Moeris could store 50 billion cubic meters of water. It could absorb and store a flood volume of 3,000 million cubic meters to be used throughout the year. Graf [29] reported that records of water storage into Lake Moeris were started in 1827 BCE using nilometers.

The Mer-Wer canal was 16 km long and 1.5 km wide. Despite the great difficulty of ancient tools, the canal was dug at a slope of 0.01° and a camber of 1:10 [3, 29]. According to the *Encyclopedia Britannica* [1], the Egyptians were still managing Lake Moeris when Herodotus visited Egypt in 450 BCE. The Lake was then 17 m above sea level and could flow back into the Nile River in periods of low floods.

Pharaoh Amenemhat III of the twelfth dynasty converted the east side of Lake Moeris into rich farmlands and built a new city called known as Crocodilopolis [28] by the Greeks due to the presence of a temple to worship the Nile crocodile divinity. The *Rhind Mathematical Papyrus* manuscript, now kept at the British Museum, is also believed to date to the period of the king of Amenemhat III. The immense work of civil engineering may have been completed under the rule of his son Amenemhat IV. Contrary to popular belief in modern Egypt, the vizier in charge of this immense civil engineering work was Kheti (not the Biblical prophet Joseph), who is listed to have served king Amenemhat III in the year 29 of his rule in a fragment of the papyrus of Lahun [30]. Vizier Kheti is believed to be the man called "He who impoverished his associates for the benefits of others" [30].

The Mer-Wer canal managed to remain self-clearing for 1,500 years [31, 32]. However, the lake was partially drained under Ptolemy II exposing a rich area of 1,200 km^2 of alluvial soils that were converted into intensive farming through a series of canals. A dam was then built to restrict the flow back into the Nile. This historical act may see itself repeated in the future in other silted up reservoirs of the Nile.

Kraemer [33] indicates that villagers in Fayum started to abandon the villages around the sixth century AD, while he reports references that would suggest that migration started in the third century AD due to the decline of the irrigation system. Although not discussed by Kraemer [33], Egypt went through a dark period of persecution under Byzantine rule, when many villagers suffering from religious persecutions due to disagreements between the Coptic Church and the Church of Constantinople simply abandoned their villages and fled to the desert. Lake Moeris eventually silted up by lack of maintenance and loss by evaporation and shrunk due to a fraction of its size, to be called today "Birket Qarun" (see Fig. 1).

In 638 AD, the Arab armies conquered Fayum in search of food before defeating the Byzantine armies of the Babylon fort (now Cairo). Eventually, Amr Ibn El-As turned his attention to re-digging the canal of the Persian king Darius between the Nile and the Red Sea for trade with Arabia, rather than reviving the Great Canal of Amenemhat III, as Egypt's wheat saved Arabia from starvation. Arab conquerors knew little about the history of Ancient Egypt and inherited the legends of the local population. *The Chronicle of John, Bishop of Nikiu* [34] (seventh century AD) showed how much Coptic legends at the time of the Arab conquest were far from historical facts and included an infinite number of errors that modern Egyptology has since dispelled. The Egyptians had long since stopped using the hieroglyphs and looked at their ancestors as mere pagans, following the conversion to Christianity. In the process, they had forgotten their history. The Arab conquerors or the local Egyptian population concluded that the remaining of Lake Moeris was once owned by Qarun mentioned in the Holy Quran. This misbelief persists today exclusively with modern Egyptians, despite the fact that the Holy Quran does not link the ill-fated story of the Qarun to the Fayum Depression or to Pharaoh Amenemhat III. The Arab conquerors renamed the canal Mer-Wer Bahr Yussef in the belief that the Prophet Joseph dug it, although such a fairy tale does not exist in the Quran.

Another evidence of the decline of The Great Lake, and the Fayum Region, according to Kraemer [33], comes from a book written in the thirteenth century. By 1240 AD, El-Nabulsi [35, quoted by Kraemer 33] wrote in his book *Kitab Tarikh al Fayum wa Biladhi* that northeast Fayum had lost many villages. Town occupied on the west were further west than the boundaries of antiquities would have allowed for Kraemer [33] therefore concludes that major changes must have happened between the eighth and thirteenth century AD. El-Nabulsi [35, quoted by Kraemer 33] noted an abandoned and silted up canal northeast of Fayum, which he called Bahr Wardan, and provided a list of ten abandoned towns along the canal.

Following the fall of the Ayubbis, Mameluks and Ottomans continued to exploit Egypt without paying much attention to the needs of the local population and the potentials of the Nile. The black plague in the fourteenth century AD killed 40% of the population of Egypt. During the French invasion of Egypt (1799–1801), French engineers explored the Fayum area. Muhammad Ali Pasha revived farming in Egypt in the nineteenth century and hired the French-born chief irrigation engineer Linant de Bellefonds. In his memoirs, de Bellefonds [36] reported that in 1820, a breach of Bahr Yussef discharged violently into Birket Qarun, removing large quantities of limestone and leaving a crater.

Garbecht and Jaritz [37, listed in Kraemer 33] suggested that there could have been similar destructive forces in periods of high Nile floods in the years of 702–704 AD and 1159 AD destroying the Itsah-Shimdmuh dike, the most important dike in the Roman-Byzantine era, causing failure for the irrigation system in southern Fayum.

In 1900–1907, an Egyptian irrigation engineer Abdul Wahbi Bey, according to Kraemer [33], decided to dig a canal over Bahr Wardan to reintroduce farming to areas that had been abandoned since antiquity. His efforts destroyed most of the archeological work of the ancient canal between Hawara and Petrie Kom No. 1.

Knowledge of the existence of the Lake of Amenemhat had disappeared in modern Egypt. The new generations of young Egyptians are oblivious of this great civil engineering work. Today nearly 350,000 people live in the Fayum Depression that was once the largest water reservoir of Egypt. It is a very interesting site with numerous small water wheels producing hydropower to drive sakkia.

There is much to learn when assessing modern reservoirs of the Nile, about the first large reservoir ever built on the Nile, its subsequent demise by siltation and lack of maintenance of feeding canals, and its transformation into a rich fertile province. As clearly stated by Bagnold [32]:

> It is doubtful whether modern textbooks of river and canal engineering convey any clearer understanding of the natural processes involved that was probably possessed by the great engineer Pharaohs of the 12th Dynasty 4,000 years ago, one at least of whose vast canals appears to have remained self-clearing for 1,500 years.

3 Modern Siltation Problems of the Nile Basin

According to a study conducted by UNESCO [4],

- Large sediment problems are encountered in most catchment areas around Lake Victoria feeding the White Nile
- Erosion of soils causes the transportation of sediments by the Blue Nile corresponding to 85% of the sediments of the Nile – these, in turn, cause siltation downstream of the Roseires, Sennar and Girba, and Aswan High Dam reservoirs
- The total inflow into Lake Victoria from stream flow and rainfall is 118 billion m^3. 86% of this input is eventually lost back by evaporation or 94.5 billion m^3. Only 23.5 billion m^3 feed the White Nile
- From the Ethiopian and Eritrean highlands, the Sobat River contributes 13.5 billion m^3. The Blue Nile 54 billion m^3 and the Atbara River 12 billion m^3 of water with principal flows coming during the flood season
- Evaporation losses over Sudan are estimated to be 7 billion m^3
- Evaporation losses over the Aswan High Dam reservoir are estimated to be 10.5 billion m^3
- Nearly 90% of the sediments entering Sudan are transported by the Blue Nile and Atbara Rivers – the annual average is 160 million metric tons
- Most of the coarse grains deposit before entering Sudan; the remaining consist of 30% clay (<0.002 mm), 40% silt (0.003–0.02 mm), and fire sand (0.02–0.2 mm). They can be classified as wash load
- Peak siltation of the AHD Reservoir occur in August–September
- Siltation is a result of rapid deforestation of the Ethiopian plateau. Prior to 1981, the sedimentation at Sennar was 4.6 million m^3/year, but increased radically to 80 million m^3/year. As a result the Sennar reservoir lost 71% of its original dead water capacity (660 million m^3) and is no longer used for irrigation purposes. It is now used as a flow regulator with limited hydroelectric capacity
- Between 1964 and 1974, the Roseires reservoir lost a capacity of 550 million m^3 due to siltation at the rate of 55 million m^3/year
- Between 1976 and 1981, siltation dropped to 20 million m^3/year, but the Roseires reservoir lost 100 million m^3 of storage capacity
- Between 1976 and 1981, siltation increased to 30 million m^3/year, but the Roseires reservoir lost 120 million m^3 of storage capacity
- Between 1981 and 1985, a drastic increase in the sedimentation occurred as siltation reached 60 million m^3/year causing a further loss of capacity of the order of 427 million m^3
- A number of agricultural development schemes in the Sudan failed due to the rapid siltation of the Roseires reservoir

Ahmed et al. [4] kept on switching from use of tons to cubic meters of sediments. This can be confusing to a dredging consultant as they did not specify the in situ density or the void ratio of sediments as they deposit in the reservoir. Lasheen [38] estimates the annual volume of sediments to be 134 million cubic meters and not tons. Abulnaga and El-Sammany [8, 10] and Abulnaga and Abdel-Fadil [9] also confirmed an average volume of 135 million m^3/year. The fact that the GERD will store 207 million m^3/year (IPoE 5]), the value of 135 million m^3/year is correct.

El-Sayed [39] in the same document speaks of 140 million tons/year and 140 million m^3/year of sediments. This confusion is not acceptable as the sediment in situ density cannot be 1,000 kg/m^3.

The Khashm el-Girba reservoir in Sudan was built in 1964. By 1977 it had lost half its storage capacity.

Although Lake Nubia captured most of the sediments since the mid-1960s, the various reservoirs have now accumulated more than 6 billion metric tons or cubic meters depending on the published reference. Whether they are 6 billion cubic meters or metric tons, there is currently no dredging fleet big enough in Egypt or Sudan to de-silt such reservoir. An entire industry of manufacture of dredging boats, pumps, and pipelines must be developed. The most appropriate country for such an industry is Egypt with its numerous manufacturing industries, while the ultimate application is in Sudan.

A number of measures have been proposed to reduce sedimentation from rivers by various authors such as Spreafico and Lehmann [40].

Catchment area measures may include:

- Soil conservation
- Settling basins and new mud ponds
- Slope and bank protection
- Bypass structures
- New off-stream storage reservoirs

In-reservoir measures may include:

- Dredging of nearby shore and creation of new arable lands
- Dead storage
- Flushing
- Hydro-suction and airlift
- Avoiding settling of fine sediments
- Controlling turbidity
- Bypassing silted-up reservoirs for new reservoirs
- Reduction of evaporation losses by weather modification to compensate loss of surface to volume ratio

At the dams, measures may include:

- Sluicing
- Turbidity current venting
- Turbining suspended sediments
- Raising the level of dam (e.g., the Aswan Dam was completed in 1902, but raised again in 1912 and 1922)
- Raising height of intake and bottom outlet structures

Some of these solutions are not practical on a large scale. For example, the Tarbela dam in Pakistan is one of the largest earth-filled dam in the world but has gradually silted up since its construction in 1976. Built on the Indus River, its reservoir is 80.5 km long, with a surface area of 250 km^2. A recent feasibility study [41] reported that the cost of de-silting the reservoir to recuperate the 30% capacity lost by sedimentation would be higher than building an entire new dam. This shows how expensive it may be to abandon reservoirs to siltation.

In 2013 the Roseires dam was raised by 10 m. Sudan also opened the new Merowe dam to increase hydroelectric power production.

The big unanswered question is whether the GERD will act as a new catchment area for coarse sediments and whether fine sediment will continue to pass through. Some experts predict that the GERD will capture 207 million cubic meters of sediment per annum according to IPoE [5] (refer to Table 2, Chap. 1 in this volume). This would leave very little sediments coming to Sudan and Egypt. However, the situation is already so drastic along all the remaining reservoirs that sediments should be dredged to recover water storage capacity and create new opportunities for farming.

At the rate of 207 million m^3/year, the GERD reservoir will almost be fully silted in 350 years. This is much shorter than the time it took to silt the Amenemhat reservoir in Fayum, Egypt.

4 Dredged Sediments as Topsoil for Food and Fodder Production

Abulnaga and El-Sammany [8, 10] and Abulnaga and Abdel-Fadil [9] discussed the potential dredging of the sediments of Lake Nubia-Nasser for food production. Test work on dredging sediments for food production remains very limited.

The mining sector moves large quantities of sediments through the construction of dedicated tailings dam once the precious ore is extracted, and the gangue must be stored away. The tailings dams are often covered with topsoil to enhance vegetation and return the soil to useful use. Bowen et al. [42] evaluated the impact of the thickness of topsoil over a period of 24 years. Layers of 0, 20, 40, and 60 cm were evaluated. The work was done in the highly arid desert of Wyoming, USA. The study covered accumulation of organic carbon (C), total nitrogen (N), available phosphorus (P), pH, soluble cations, electrical conductivity (EC), and cumulative water infiltration.

- Species richness and diversity were the highest at 0 cm topsoil.
- Species richness and diversity were the lowest (25) at 60 cm topsoil.
- Percent canopy cover of grasses was highest (25%) at 60 cm topsoil.
- Percent canopy cover of grasses was lowest (15%) at 0 cm topsoil.
- Percent forb cover was highest (6%) at 0 cm topsoil and lowest (2%) at 60 cm topsoil (forb is an herbaceous flowering plant that is not a graminoid (grasses, sedges, and rushes).
- Seeded species cover was highest (12%) at the 40 cm topsoil, but was not significantly higher than other depths of topsoil.

- Above-ground biomass was similar between 40 and 60 cm topsoil and higher than top soils at 0 and 20 cm.
- Plant species and diversity decreased with increasing topsoil, while biomass increased.
- Organic carbon mass in the soil was the greatest at the 60 cm topsoil depth.

The climate of Wyoming is different and much colder than the deserts surrounding the Nile Valley, but the study indicates that the relationship between biomass accumulations and nutrient enrichment is complex. At an industrial level where biomass accumulation is important, a topsoil depth of 40–60 cm should be considered.

Abulnaga and El-Sammany [8, 10] conducted a survey with Egyptian agronomists and recommended:

- A minimum topsoil depth of 50 cm for food production
- A minimum topsoil cover of 25 cm for cattle ranching

The presence of trace elements and heavy metals could impact schemes to farm by application of sediments dredged from the Nile. Lasheen [38] evaluated the distribution of cadmium, cobalt, copper, and manganese, and zinc was assessed by catching fish from Lake Nasser (see Table 1). In trace elements, these metals play a major component to the nutrients of aquatic life. However, in large quantities, they become toxic as they accumulate in vital organs.

The distribution of trace elements varies on a seasonal basis, as well as with depth of the reservoir. The concentration was found to be below the criteria of water quality of the US Environmental Protection Agency. The sediments of the AHD Reservoir should, therefore, be suitable as topsoil to grow new plants on its shore.

There is no published data in the literature on extracting sediments from the many reservoirs along the Nile to grow food, by enriching poor soils. It is, therefore, useful to review experiments carried out with other reservoirs.

Canet et al. [11] studied the dredging of sediments from Albufera Reservoir in Eastern Spain. The feasibility study focused on the application of three rates of 180, 360, and 720 t/ha corresponding to different sources of contamination, through mixing with soils from surrounding areas. Lettuce (*Lactuca sativa* L) and tomato (*Lycopersicon esculentum* Mill) were studied. The addition of sediments improved the water retention capacity of the soils but increased salinity and heavy metal content. Significant absorption of nutrients by the plant was noticed without the absorption of heavy metals. The yield of lettuce improved while the yield of tomato was not affected. The authors concluded that application of bottom sediments to sandy soil would be a recommended practice to dispose of dredged material.

Table 1 Range of trace elements measured by Lasheen [38] for measurements done in 1976

	Lake Nasser (μg/L)	Lake Nubia (μg/L)
Cadmium	0.4–3.14	0.74–4.89
Cobalt	0.6–5.64	0.3–8.14
Copper	3.38–18.92	0.87–13.8
Zinc	8.45–42.49	0.67–24.96
Manganese	16.67–384.84	1.84–224.15

The government of Zimbabwe announced a national program to dredge sediments by dam de-siltation for food production [43]. The program should involve 2,000 farmers under the “Targeted Command Agriculture Program.” The aim is to produce 5 metric tons of grain (wheat and maize) per hectare. It is unknown if this program was implemented due to political instabilities with the toppling of President Mugabe in 2017.

Gamboa [12] examined dredging sediments from the Gallito Ciego Reservoir on the Jequetepeque River in Peru. The reservoir has a surface area of 14.2 km^2 and a mean depth of 40 m. It had lost 70% of its dead water volume to sediment by 2007 when its bottom outlet became blocked. Physical parameters such as grain size distribution, chemistry, and pollutants were assessed for agricultural applications. Heavy metal concentration was found to be below the toxic threshold. The sediments were considered to be suitable as a soil additive or as a material for the manufacture of building material.

The Rožnów Reservoir is an artificial lake built in Poland between 1935 and 1941 to regulate the Dunajec River and to produce hydroelectricity. Wiśniowska-Kielian and Niemiec [13], experimented with enriching light weakly acidic soil with sediments dredged from the Rožnów Reservoir and assessed the accumulation of lead and cadmium in the plant biomass. Sediments were applied at 10–100% of the substratum soil.

The test plants consisted of oat and narrow leaf lupine cultivated after each other. Samples were compared with plants grown in contaminated soils, where the toxicity had exceeded threefold the permissible limits to use the plants as fodder for animals.

- 10% addition of sediments caused visible limitation of accumulation of lead and cadmium in aerial and root biomass.
- Larger sediment addition (60% or more) reduced metal accumulation only in aerial oat biomass.
- Bottom sediment addition to light and weakly acidic soils improved their suitability as fodder for animals.

The authors recommended the application of sediments dredged from the bottom of the Rožnów Reservoir to contaminated and poor soils to reduce the intake of poisonous metals and improve the ability to grow plants for fodder.

Corn or maize is an important crop for human consumption and as fodder for husbandry. Wiśniowska-Kielian and Niemiec [14], assessed the addition of sediments dredged from the bottom of Rožnów Reservoir to light very acid soil and assessed the accumulation of trace elements in the biomass of maize (*Zea mays* L). Sediments were applied at 1–14% of the substratum soil. The trace elements assessed consisted of nickel (Ni), lead (Pb), chromium (Cr), and cadmium (Cd).

Sediments added at 1–4% of the substratum caused an increase of nickel, lead, and chromium in the aerial parts of the plant. Larger addition (>6%) reduced the accumulation of nickel, lead, and chromium. Application of sediments above 2% caused a reduction of cadmium absorption.

The addition of dredged sediments to light and very acid soils lowered the absorption of trace elements by corn and should be used to improve the forage quality of plants.

Wiśniowska-Kielian and Niemiec [15], discussed further the dredging of sediments for improving food production by dredging and observed:

- Bottom sediments are the main link in matter cycle in the water ecosystem and constitute a reserve for many elements.
- An increase in metallic element contents in sediments as a result of water self-purification.
- Even sediments from relatively clean waters may still contain large amounts of harmful substances.
- Dam reservoirs situated on mountain rivers usually contain less organic material than reservoirs in lower lands.
- Dredged bottom sediments from natural or artificial reservoirs reveal alkaline reactions and sizeable fraction of silt and clay.
- The alkaline reaction is beneficial to treat poor and acid soils.
- Although sediments can be dredged, they must be managed to comply with government codes on limits of trace elements concerning the quality of soils.
- Abela and Favila [16] described a successful revegetation of barren tailings soils from a nickel mine using native species from the Philippines. The local grass species were grown first in potting bags prior to planting and four shrubs were grown directly. The soil was too soft for use of heavy mechanical equipment, so plants were plotted manually. The soils suffered from lack of nitrogen, potassium, and phosphorus. A triple fertilizer was applied while vermicompost was applied to introduce microorganism. Carbonized rice hull (CRH) was mixed with the soil media. Composting material consisted of rice hull (at 70%) and cow dung (at 30%). The vermicompost is prepared by introducing an earthworm and takes 2 months to convert the rice hull and cow dung. CRH was produced by controlled combustion of rice hull by pre-perforated metal drums. In the bottom half of the drum with wood, the rice hull is added on top. Abela and Favila [16] listed the number of plants that were successfully tested in these weak soils such as:
- Humidicola (*Brachiaria humidicola*) – a strong creeping perennial grass that grows well in infertile soils
- Stylo (*Stylosanthes* sp.) – a 40–70-cm-tall legume with woody base that is very well adapted to clay soils and sustains long dry seasons
- Napier grass (*Pennisetum purpureum*) as suitable fodder for animals that grows in wet areas
- Banana (*Musa* sp.) with leaves grow fast and can attract fauna

This technique could be adapted to Egyptian and Sudanese conditions on the shore of the Nasser-Nubia Lake, by using the dredged sediments as topsoil and developing simple methods of seedling and development of vermicompost. While wood is scarce in Nubia, solar energy is abundant and solar ovens can be built for producing CRH.

The development of special crops for the lands of the Nile banks from Burundi, Uganda, Eritrea, Ethiopia, South Sudan, Sudan, and Egypt will be the work of numerous specialists. The de-silting of the reservoirs of the Nile may need to be at the same scale as the reconstruction of the Louisiana coast in the USA, costing billions of dollars.

5 Proposal for Establishing Small Communities by De-silting and Dredging

One of the largest dredging projects ever taken in the world to rebuild ecological habit is called COAST 2050. Between 1956 and 2000, the coast of Louisiana lost 3,950 km^2 due to ocean-induced erosion according to Reed and Wilson [20]. In 1989 the State of Louisiana adopted Act 6. The act proposed to invest US$15 billion over 15–20 years to restore the Louisiana coast [21].

In the 1990s, the Federal Government of the United States enacted the "The Coastal Wetlands Planning, Protection and Restoration Act" (CWPPRA pronounced kwĭp-ruh) to devote funds for the restoration. It proposed to rebuild the coast of the state of Louisiana, in the USA (Fig. 2), by dedicated dredging of existing lakes and transporting sediments through dedicated slurry pipelines. Such a large investment was justified because an economy worth $150 billion was in danger, including numerous oil wells and pipelines.

COAST 2050 is the largest shore restoration project in the world, and it involved a large number of experts from various agencies and universities such as:

- Louisiana Department of Natural Resources
- Louisiana Cooperative Extension Service
- US Environmental Protection Agency
- US Army Corps of Engineers
- Louisiana State University
- National Resources Conservation Service
- Coastal Environment, Inc.
- University of New Orleans
- National Oceanic and Atmospheric Administration
- Louisiana Department of Wildlife and Fisheries
- A number of engineering firms and non-governmental organizations
- Representatives from the oil and gas industry

The Governor's Office of Coastal Activities, the Office of Coastal Restoration and Management in the Department of Natural Resources, and the State Wetlands Authority were established.

Plants were seeded to halt the erosion of the coast such as smooth cordgrass (*Spartina alterniflora*), a genetically modified version [22]. Plant biodiversity is critical for successful coast restoration [23].

There are two aspects to encourage community development through de-silting the Reservoirs of the Nile:

- Serving existing communities downstream of the reservoir by re-establishing water storage capacity to provide water in periods of draught and low floods
- Building new communities along the shores of the AHD Reservoir

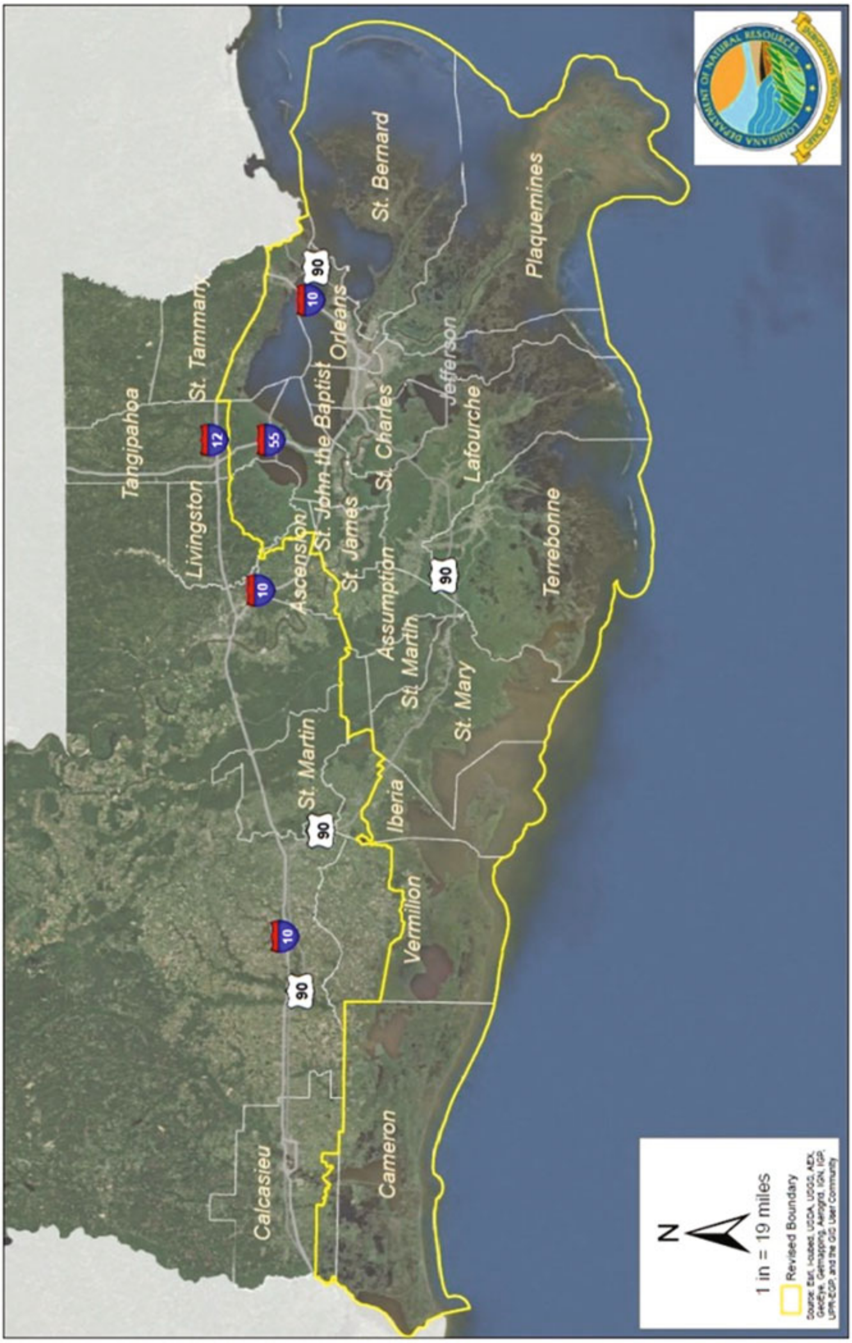

Fig. 2 Shores of Louisiana subject to restoration by dredging and planting – reproduced from http://mississippiriverdelta.org/coast-2050s-lasting-impacts-on-coastal-restoration/

Over the last 60 years, Egyptian engineers have realized large reclamation deserts. The Tahrir Province, west of the Delta, reclaimed 600,000 feddan (2,520 km^2) of lands [44].

The Egyptian government also launched a number of initiatives in the 1980s and 1990s to allocate 5 feddan to university graduates and 2.5 acres to landless farmers to reclaim desert lands, east and west of the Delta, and in the Fayum Depression. According to Sims [44], these small-scale projects accounted to 32% of the reclamation projects. Unfortunately very few university graduates took the challenge of moving to the desert, but eventually, 250,000 small farmers were settled, between 1987 and 2003. This number is small for a country with an annual population growth of a million people. It reflects the difficulty of establishing new infrastructures, such as health and education, roads, and power. Some communities such as the New Basaisa project in the Sinai rely on solar energy [45].

A number of megaprojects have been announced over the years focusing on bringing water to the Uweinat region in South Egypt. The Sinai through the Salem canal, a large deviation project, linked the Toshka Depression with the AHDR. Many of these megaprojects faced the problem of poor soils.

Ironically, small farmers have been able to reclaim 1.3 million feddan (5,460 km^2) of desert land, as small plots, through a process called “Wadd El-yad = اليد وضع,” allowed by the 1947 Code. These small entrepreneurs are usually ignored by the local authorities and do not get much support in terms of new infrastructure, as the process of transfer and registering ownership requires 15 years of continuous occupation [44].

Another scheme that was successful in creating numerous employment opportunities was the “Law of Cooperatives for Development of the NGO Community”. It allowed small investors, farmers, and inhabitants of villages to pool their resources and employ local women in textiles and knitting industries.

The Egyptian experience shows that government intervention can be successful in some cases such as the Tahrir Province, which faces insurmountable problems in other cases, but ultimately should involve small farmers as they have demonstrated great innovation in Wadd El-yad[1] processes.

The selection of the site must match the depth of the sediments and the distance to shore. Certain areas such as Arkeen near the border of Sudan (331 km south of Aswan) can be deep from few meters on the west side to as much as 35 m (Fig. 3). At Abu-Simbel (282 km south of Aswan), the depth on the east shore is 30 m but on the west side 70 m (Fig. 4).

The depth of the AHDR is therefore not uniform (see Figs. 3 and 4). The cost of dredging can be reduced by selecting shores where sediments are shallower on the east or west banks of the reservoir.

Having determined that the depth for dredging be between 10 and 60 m, the second challenge that the engineer must face is the high plasticity of the clays. Pending

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[1] Wadd El-yad means someone used a part of the public land for any purpose and for a few years then he said I am the owner of this land. The government asked him to pay for this land to confirm his ownership of this land.

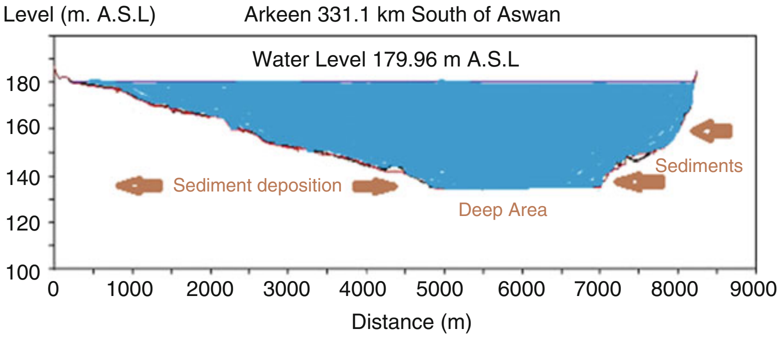

Fig. 3 Cross section of the Nile at Arkeen, 331 km south of Aswan (after Abulnaga and Abdel-Fadil [9]) for the year 2002

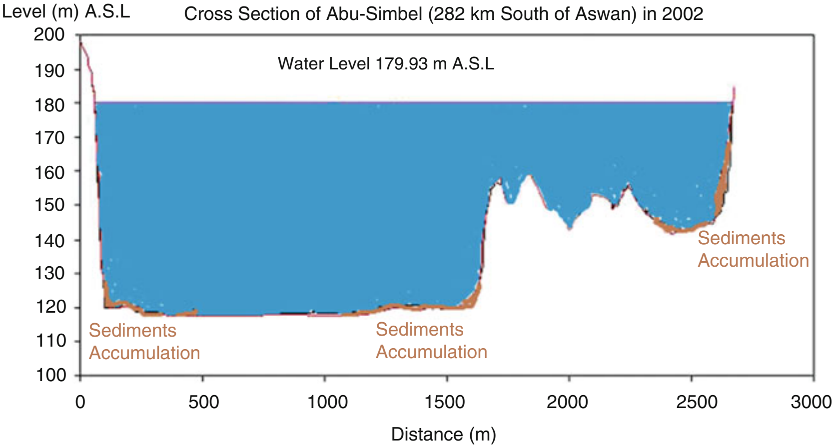

Fig. 4 Cross section of the Nile at Abu Simbel 282 km south of Aswan (after Abulnaga and Abdel-Fadil [9]) for the year 2002

confirmation of the plasticity index of the clays (e.g., Smectite), of the AHDR, it would be safe to assume that there is, therefore, a definite risk for balls of clay (Fig. 5) to form, based on the analysis of Woodward for the clay sediments of the Nile.

The previous calculations [8–10] did not account for the risk of formation of balls of clay and would require a special dredging system capable of breaking the clays as discussed by Vandycke [46]. The clays evaluated had an in situ density (ρ_{situ}) of 2 T/m^3, liquid limit (LL) 55%, plasticity limit (PL) 22%, and plasticity index (PI) 33%. They used a drag head that cuts by applying weight – but this did not work so they added high-pressure water jets operating at 380 bars and jetting at 250 to 380 m/s to pulverize the clay. The DRACULA system is patented, so Egyptian engineers would have to develop an alternate jet cutting system for the clays of the Nile.

Fig. 5 Balls of clays formed during dredging with a range of diameter of 125–200 mm

There are other suppliers of dredging equipment with jet suction such as Rohr-Idreco, but the applied jet pressure is only 18 bars. Dragflo an Italian manufacturer produces small submersible with cutters and pressurized jets.

The pressure of a jet to cut through the clays of the Nile needs to be assessed through field testing. The information is not available.

The dredging done in Sudan by British engineers in May 1911 using the dredger manufactured by Lobnitz & Company Ltd. of Renfrew, Great Britain [47], proved that clay cutting was essential. It also proves that dredging is still possible in the Nile without high-pressure jetting.

However, it becomes critical to assess the risk based on more recent information on plasticity index from Toshka published by Labib and Nashed [48], namely:

- Particle size smaller than 0.002 mm (clay fraction) ranged from 18.51 to 85.81%
- Liquid limit $44.70\% \leq L_L \leq 104.50\%$
- Plasticity index $24.30\% \leq PI \leq 82.98\%$
- Activity PI%/clay fraction % 18.51–85.81
- Density of sediments $2{,}580\ \text{kg/m}^3 \leq \rho_s \leq 2{,}650\ \text{kg/m}^3$

Wilson et al. [19] described a method to complete the hydraulic analysis of dredged balls of clay with an average diameter of 100 mm. They reported that K. Oudmaijer of the Netherlands reported that balls of clay with an in situ density of 1,790 kg/m^3 with a diameter of 100 mm caused a mechanical friction factor (μ_s) of 0.31.

Leschinsky et al. [18] conducted their tests up to 2.4 m/s as the realistic regime to move the balls of clay, although the main flow can be twice this magnitude. A similar value is calculated by Wilson et al. [19], who indicated that the particle diameter of 100 mm (4″) had a velocity at the limit deposition that can be extrapolated from the size of 30 mm (1.25″), by stating that the change from 30 to 100 mm is essentially the same as from 9 to 30 mm.

A popular pipe diameter for dredging is 600 NB (called 24″) with a pipeline inner diameter of 590 mm. High-density polyethylene (HDPE) is popular as it is easy to relocate. In Egyptian and Sudanese conditions, its pressure rating must be de-rated for temperature.

Some assumptions can be made for a commercial dredging system:

- Operation close to 1,300 L/s (US 20,000 gpm)
- Five pumps on the pipeline
- Shore buffer zone 2 km by law, so average pumping distance 5,000 m
- 600 mm NB pipeline
- The in situ density of 2,000 kg/m^3
- Clay ball size 0.5–125 mm
- Suction depth 40 m
- Discharge static head 15 m to account for hills or bank
- Five pumps in series for a total differential head of 200 m
- Topsoil to be deposited 50 cm for farming

Table 2 shows that it is critical to pulverize the clay down to 0.5 mm lumps. In addition to the pumping power, the power for pulverization must be added. With the proper cutting of clay by jetting to 0.5 mm, the dredging operating 4,000 h can extract 4.5 million m^3 of sediments and reclaim 2,187 feddans. However, failure to cut the clay will drop the volume of dredged sediments to a tenth (see Fig. 6).

The calculations show that each pump will consume 1,000 kW on the average. The pumping cost is between 2.1 and 16.4 kWh/m^2. This is equivalent to 8,800 kWh/feddan if the clay is reduced to 0.5 mm balls at the suction and to 68,500 kWh/feddan if it is transported as stiff and large balls. The cost of fuel and energy is going through important changes in Egypt as subsidies are removed. In the USA, certain hydroelectric dams produce power at $0.05/kWh, while in some areas in Europe, electricity is produced at $0.30/kWh.

Once the topsoil is installed, there are certain plants that help fix nitrogen. The dredging system and pipeline can then be relocated to a new site.

Also there is the cost of labor to operate the dredging system and the initial capital to purchase the equipment, pipe, and pumps.

The abrasivity of the sediments will determine the lifespan of the HDPE pipes. Clay is not very abrasive, but the presence of silica in the form of fine to coarse sand either transported by the Nile or blown by the wind toward the reservoir will cause wear of pumps, valves, and pipes.

An emerging technology that could decrease the requirement for pulverizing clays is the clay log pipeline [49], but it has not seen commercial application yet.

Table 2 Dredging parameters and reclaimed land

Ball or particle size of clay (mm)	In situ density of sediments (kg/m^3)	Slurry flow rate (m^3/h)	TDH of dredging system (m)	Discharge distance (m)	Volume of sediments removed (m^3/h)	Total Volume removed for 4,000 h/year (m^3)	Acreage gained with 50 cm topsoil (feddan)	Pumping power (kW)	Cutting power (jetting) (kW)
125.0	2,000	4,498	200	5,000	119	474,610	226	3,866	To be determined
30	2,000	4,634	202	5,000	122	489,920	233	4,024	To be determined
4.2	2,000	4,527	200	5,000	214	857,360	408	3,932	To be determined
0.5	2,000	5,100	190	5,000	1,148	4,593,000	2,187	4,776	To be determined

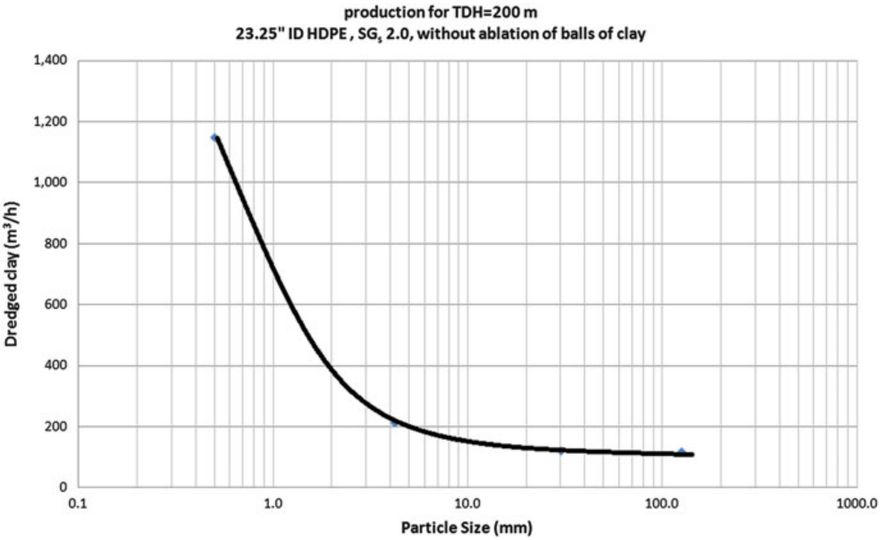

Fig. 6 Effect of the diameter of balls of clay on dredging rate – assumed pipeline length 5 km, static head 15 m, suction from a depth of 40 m

Each new community will be around one pipeline and will get 2,200 feddan. Each pipeline will consist of four pumps in series with 1,250 kW motors. Twenty separate pipelines at different points would be installed at different points on the east and west shores of the AHDR. This way 10 million cubic meters will be dredged each year to reclaim 44,000 feddan.

De-silting the reservoirs of the Nile in Egypt and Sudan must be done on a multidisciplinary level to be successful (Fig. 7). It will require a number of solar energy schemes, wind power farms, roads and fuel pipelines, schools, and hospitals. The presence of new populations and new communities will provide the technical expertise and the labor force to diverse from farming to industrial projects such as a new dredging industry, manufacture, and repair of pumps and pipes.

A large solar energy project is under construction at Benban, in the Aswan area, rated at 1,900 MW with investment worth $2.5 billion [50]. But small communities can also follow the model developed at Bassaisa in the Sharqia Governorate, East Delta, and New Bassaisa since the 1970s under the supervision of Professor Salah Arafa [45]. These eco-villages are heavily dependent on solar energy. Other sustainable models have been proposed [51].

One particular problem specific to the AHD Reservoir is that most of the silts have accumulated in the past in Sudan or in Lake Nubia. Some mechanism needs to be developed to dredge these sediments by collaboration between Egypt and Sudan (see Fig. 8). This may take the form of Egyptian-Sudanese agribusiness enterprises. If Sudan cannot invest in such schemes, it could be paid back for the sediments in the form of a share in agricultural production or paid a rate per cubic meter of sediments dredged. The

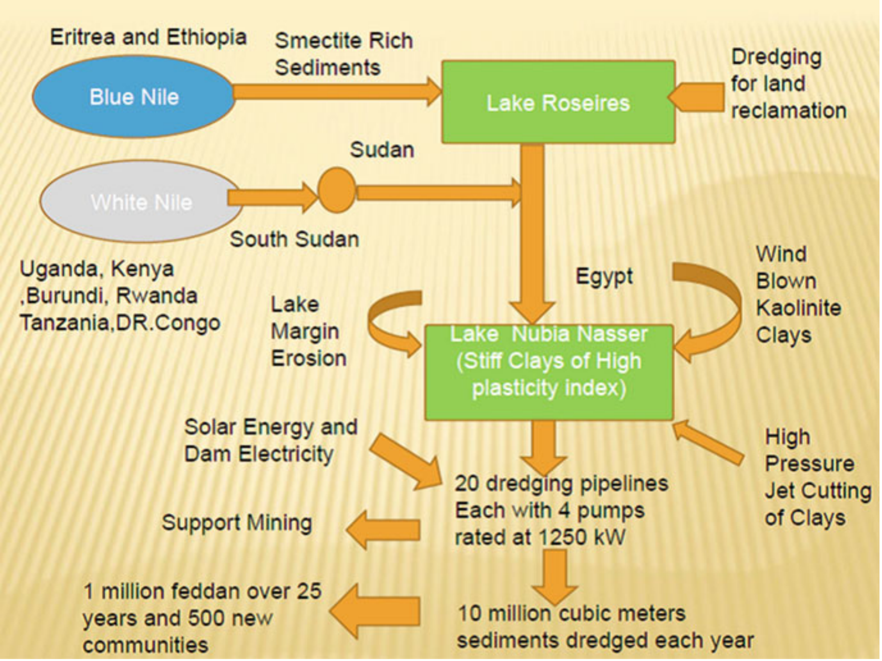

Fig. 7 Flowchart for dredging 10 million cubic meters of clays each year through 20 dedicated pipelines to create 500 new communities and reclaim 1 million feddan over 25 years

sediments would be considered a sort of raw material or mining commodity. Dredged material used as a form of source of gravel or sand is often paid by volume.

There may also be some mining opportunities that would benefit from the construction of slurry pipelines bringing water and topsoil to mining communities [51] in both Egypt and Sudan. The Lake Nasser shore has a number of small quarries, but an iron-steel project was once announced 50 km east of Aswan [52]. Iron ore was discovered near Aswan in 1939 [53]. It was shipped in the 1960s to the smelter of Helwan but was discontinued once the Bahria ores were discovered. Some of the ore deposits were submerged by the construction of the AHD under Lake Nasser.

Salam et al. [54] reported that remote sensing identified potential areas for iron ores at Kurkur and Abu-Simbel and in Toshka. Iron ore near Aswan is found in Wadi Temsah, Wadi Kharit, Wadi Beida, and Wadi Umm Huqban. Wadi Temsah is on the shore of Lake Nasser.

Wadi Kharit is in the eastern desert at an elevation of 103 m above sea level. It could potentially be a site for a micro-hydropower station since it is lower than Lake Nasser. Power can then be used for mining. Wadi Umm Huqban is however at an elevation of 234 m ASL, so water could be returned to Lake Nasser by gravity after depositing the sediments.

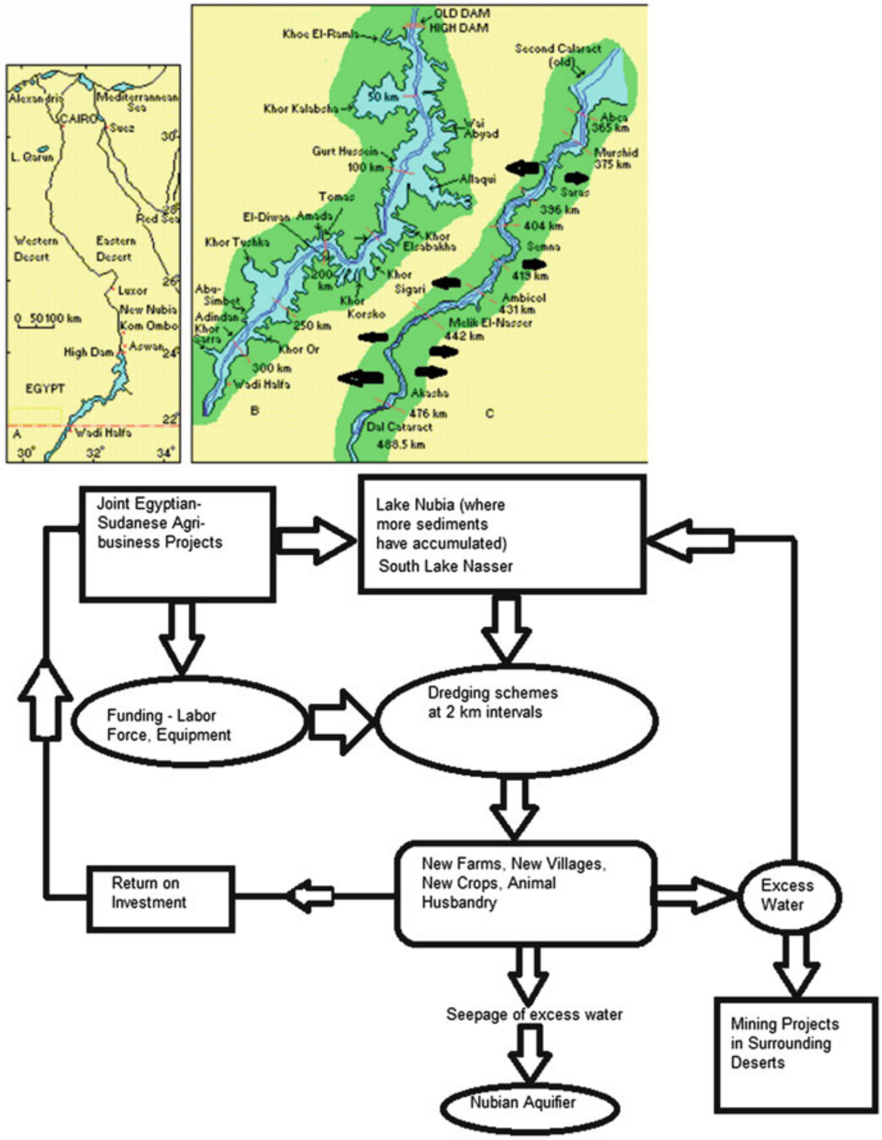

Fig. 8 Flowchart for collaboration between Egypt and Sudan to dredge Lake Nubia and South Lake Nasser

6 Conclusion

The GERD is expected to capture 207 million cubic meters of sediments each year. In the immediate future, the silted-up reservoirs of Roseires and Nubia will have their inflow of sediments reduced. Although experts disagree on the extent of siltation, it is believed that nearly 7 billion m^3 have been deposited in the last 60 years among the various reservoirs in the Nile, mainly in Sudan.

A fleet of 20 dredging systems involving 80 dredging pumps could then remove 100 million m^3 of sediment and reclaim 44,000 feddan/year (or 185 km^2/year) by pumping dredged clays over a distance of 5 km from the point of de-silting. These numbers over a span of 25 years could reclaim more than a million feddan (4,200 km^2), for an applied thickness of 50 cm topsoil. However, if the plasticity index of the clays is ignored at the design stage, the project will turn into a failure.

There are large quantities of water moved in the process. Some quantities may seep and replenish the Nubian aquifer. Other quantities can be absorbed by plants that facilitate fixing the clays while consuming the water, such as rice and sugarcane. Excess water can be returned to the local reservoir by gravity if the new lands are higher through drainage trenches or by pumping back. Some water will also be lost by evaporation but could be recovered by weather modification through cloud seeding or fog capture. Joint Egyptian-Sudanese agribusiness projects are encouraged since most sedimentation has accumulated in Lake Nubia and south of Lake Nasser.

Past experience with large dredging and re-cultivation project such as COAST 2050, in Louisiana, USA, had costs in the amount of $15 billion and required very strong collaboration with scientists and private and public sector stakeholders. Egypt and Sudan need to develop together a similar vision and allocate dedicated funds and create a dedicated agency. The cost may be high but unavoidable.

7 Recommendations

It is recommended that the governments of Sudan and Egypt collaborate in their efforts to de-silt the reservoirs in the Nile. If the technology of cutting the Smectite-based clay deposits can be developed to the point that balls do not form in the dredging pipeline, millions of cubic meters of sediments could be extracted each year.

It is therefore recommended to promote the development of a dredging industry in Egypt and Sudan. Mutual collaboration between the experts should bring the cost to a level where they can be managed as part of a holistic approach to create new economic development. Further feasibility and pilot projects should be conducted and compared to other options such as raising the dams on existing reservoirs.

The calculations show that the governments should encourage the manufacture of local dredger and dredging pumps as it would take 80 dredgers and 240 boosting pumps with 1,250 kW engines or motors to dredge 100 million tons of sediments per year and reverse 60 years of siltation.

Despite past failures to revive the mining of iron ores near Aswan, new deposits have been identified around Lake Nasser. It is, therefore, recommended to link efforts of de-silting, the creation of new communities with local mining opportunities. The availability of a local labor force in new communities and a rich supply of food should be made available for new energy and mining projects.

To emulate the experience gained with COAST 2050 in the USA, a $15 billion program over 20 years to dredge inner lakes and rebuild the shores of Louisiana, a joint agency, should be established involving:

- Irrigation and water resources ministries in both Egypt and Sudan
- Local universities
- Private sector manufacturers of engineering equipment
- Public sector manufacturers of equipment
- Dredging companies
- Ministries of Agriculture
- Mining sector stakeholders
- Fisheries
- Producers of energy such as the local hydroelectric dam management authorities
- Economy and trade agencies

The funding of such a large project could be recuperated through newly created farming, animal husbandry, and industrial brick manufacture activities.

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Harvesting the Skies of Egypt: An Option to Recover the Evaporation Losses from the Aswan High Dam Reservoir

Baha E. Abulnaga

Contents

Abstract The Aswan High Dam Reservoir (AHDR) is one of the largest man-made reservoirs with a surface area of 6,000 km^2. It was built in the aridest zone of Egypt and Sudan. Evaporation losses range from 5 to 10 mm/m^2/day throughout the year and average 7.4 mm/m^2/day leading to an estimated loss of 16 km^3 or 20% of the annual consumption of water by Egypt for farming, industrial, and domestic applications.

These losses cannot be prevented and are difficult to reduce. Schemes to compensate for the evaporation, namely, weather modification and water harvesting from the air, are examined in this chapter. Evaporation losses are transported at low levels of a few hundred meters but also at heights of 1,500–4,000 m as there are different patterns of lower and upper winds.

For the lower levels, there are two important technologies that have grown in other countries to extract water vapor from the air: fog harvesting and dew harvesting. The success of these technologies is very much dependent on the geography of the site

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and its climate. Efforts to utilize nocturnal radiation for refrigeration and natural ice making at night are not a recent phenomenon; the Ancient Egyptians and Ancient Persians were champions of nocturnal refrigeration where the intense cooling radiation to a black sky was used to freeze water and produce natural ice. This technology can be adapted in an Egyptian context. Fog collectors must be capable of resisting the strong “khamsin” windstorms between March and June.

Egypt has an interesting pattern of inversion of temperature between night and day. This leads to the formation of dew and fog and low clouds particularly over the Delta and Cairo during certain periods of the year and just for few hours to few days but also to vigorous vertical currents rising to 4,000 m and transporting evaporated water.

The direction of the winds over the Aswan High Dam Reservoir tends to blow from the north and northwest. This would suggest that water lost by evaporation tends to flow along the axis of the reservoir south toward Upper Nubia or Northern Sudan and southeast toward the Egyptian Eastern Desert, the Halayeb region, and the Red Sea coast. The Hadley cell pattern over the Earth forces the water lost by evaporation at the AHD Reservoir back to the equator. Coriolis forces due to the rotation of the Earth curb this flow slightly toward the east. While the Grand Ethiopian Renaissance Dam (GERD) will deprive the AHD Reservoir of waters, the AHD Reservoir will continue to feed back the sources of the White Nile and the Blue Nile with water by evaporation. The governments of Egypt and Sudan should embark on weather modification to capture these losses. The clouds are overcast at 5–25% over Lake Nubia and Lake Nasser and will require a carefully planned approach.

The technology of weather modification can also be tested on the northern coast of Egypt from Salum to Rafah and certain parts of the Delta where annual precipitation ranges from 50 to 200 mm/year. The Ancient Egyptians, the Greek, and Roman rulers had developed in the past a complex system of deep wells and water storage schemes for storing rainwater that should be revived in parallel to weather modification schemes.

Cloud formation over the AHDR is at its peak during the flood season of July and August, while it is at a minimum over the north coast of Egypt. This opens an opportunity to maximize utilization of aircraft all year round with an emphasis on the north coast in the winter and on Lake Nasser in the summer. Weather modifications must be viewed as a carefully planned project. The conditions favor high-altitude cloud seeding at 4000 m to avoid the errors and pitfalls of low-altitude failures.

Egypt and Sudan do not have currently a program for weather modification or cloud seeding. This chapter is, therefore, an attempt to open the discussion on the merits of this technology.

Keywords Aswan High Dam Reservoir, Climate of Egypt, Cloud seeding, Dew harvesting, Evaporation losses, Fog harvesting, Hadley cell, Mist oasis, Nocturnal radiation, Weather modification

1 Introduction

The climate of Egypt is a complex juxtaposition of Saharan climate in Upper Egypt, Mediterranean climate in Lower Egypt at the upper elevation in excess of 2,000–4,000 m, and potential six zones for climates at a surface level ranging from Mediterranean to semiarid to fully arid [1]. The Gebel Elba Park in the Halayeb region experiences at low levels precipitation of 50 mm/year and at high altitudes, at mountains rising to 1,450 m, precipitation of 400 mm/year and is a prime candidate for weather modification. The Red Sea coast, Eastern Desert of Egypt, Halayeb triangle, and Upper Nubia in Sudan are zones void of population centers, inhabited by pastoral nomads, but extremely rich in minerals. It is also rich with canyons called wadis that could be used to direct water precipitated from cloud seeding. North Sinai at ground elevation experiences limited precipitation of 63 mm/year, but at a high elevation such as Gebel Katherina, it experiences precipitation in excess of 300 mm/year in the form of snow. Throughout the peaks of the mountains of Egypt, mist or fog oases form natural refuges for flora and fauna in the midst of extremely dry climates.

While the Aswan High Dam Reservoir has protected Egypt in periods of acute drought, its extended surface of 6,000 km^2 causes a tremendous evaporation loss of water amounting to 20% of the entire domestic, agricultural, and industrial consumption.

In the last 50 years, a number of efforts have been made to catch moisture from the air [2]. Originally developed for the driest coastal desert of the world, the Atacama, fog collectors have slowly been spreading to other countries. They were developed originally of a flat configuration, but new interesting designs coming out of Ethiopia are of a strong tower configuration that could be adapted for the harsh environment of Egypt with strong sandstorms.

Dew forms on cold nights on the glass shields of millions of cars in Egypt, but there are no collectors to collect it into potable water, although there is archeological evidence that the Ancient Egyptians practiced dew collection through a special arrangement of collecting stones. They invented nocturnal refrigeration to exploit the radiation cooling to the black sky. Special dew collectors can, therefore, be designed for modern times.

The greatest challenge is to slow down the movement of water vapor from evaporation back to the tropics. Northerly winds due to the Hadley cell and Coriolis forces due to the rotation of the Earth force the moisture toward the Red Sea coast and the equator feeding back indirectly the very same GERD that will deprive Egypt from a percentage of water it used to receive. Weather modification is, therefore, an option if not the only option to capture some of this valuable moisture through collaboration between Egypt and Sudan. There is no model to copy, and both countries will have to embark into experiments of their own. The conditions favor high-altitude weather modification at 4000 m with very careful planning.

Cloud formation over the AHDR is at its peak during the flood season of July and August, while it is at a minimum over the northern coast of Egypt. This opens an opportunity to maximize utilization of aircraft.

2 Climate of Egypt

There are a number of classifications for the climate of Egypt. Traditionally, Egypt was considered to have a Mediterranean climate over the Delta and Cairo zone (Lower Egypt) and Saharan climate starting at latitude south of Cairo over Upper Egypt. The dichotomy of these two climatic zones caused Ancient Egyptians to call their country "Tawi" or The Two Lands, each with its own white and red crowns, symbolizing two kingdoms united by the ruling pharaoh.

The spring and autumn seasons are short, so the winter is considered to start in November and last until April. During this season, the Sahara experiences a high air pressure zone, while Central Africa experiences low pressure. This results in a northerly wind flowing almost from the north Mediterranean Sea to the equator. Frequent passages of depression along the Mediterranean coast tend to break the northerly winds over Lower Egypt causing southerly winds (moving from the south), changing to the west and northwest around the depression. Heavy rains occur then over Lower Egypt concurrently with depressions over Egypt and the Sinai Peninsula. Areas of high pressure over the Balkans in Southeast Europe can induce strong northerly winds over the Nile Valley moving south into Sudan and South Sudan [3, 4].

As the winter ends in April, air pressure falls over North Africa. High-pressure zones move northwestward into the Mediterranean Sea, while the low-pressure belt and the Intertropical Convergence Zone (ITCZ) move northward into Sudan. Depressions form with southerly winds (winds originating in the south) in April to June, causing sandstorms called "khamsin" with occasional rainfalls behind the depressions. In summer, the monsoon low-pressure zone over northerly India extends westerly and northerly winds tend to prevail over Egypt.

These patterns of wind are critical for harvesting water evaporated from the Aswan High Dam Reservoir.

In an effort to understand better the potential for renewable energy near the ground where wind power and solar energy can be harvested, the Egyptian Organization for Energy Planning [1] formulated six climatic zones:

- Mediterranean, along the northern coast from the border of Libya to Gaza in Palestine, some 50 km wide parallel to the coast
- Semi-Mediterranean, a band south of the Mediterranean climate zone up to Middle Egypt, 200 km south of Cairo, in the Western Desert and into the North Sinai and coastal regions in southern Sinai
- Red Sea climate on the coasts of the Red Sea from Suez to the border of Sudan
- Semiarid zones partially in Sinai and covering most of the Eastern Desert
- Arid desert zones in Upper Egypt up to Luxor and the Western Desert

- Arid climate covering the Aswan region, the AHD Reservoir, and Gilf Kebir areas (Fig. 1)

2.1 Wind Patterns

The recovery of evaporated losses depends on the nature of the climate, relative humidity, wind regimes, size of droplets, coalescing chemicals used, altitude of evaporated droplets, and cloud formation.

It is critical to differentiate between:

- Surface winds at low altitude (<700 m)
- Upper winds (>700–1,000 m)

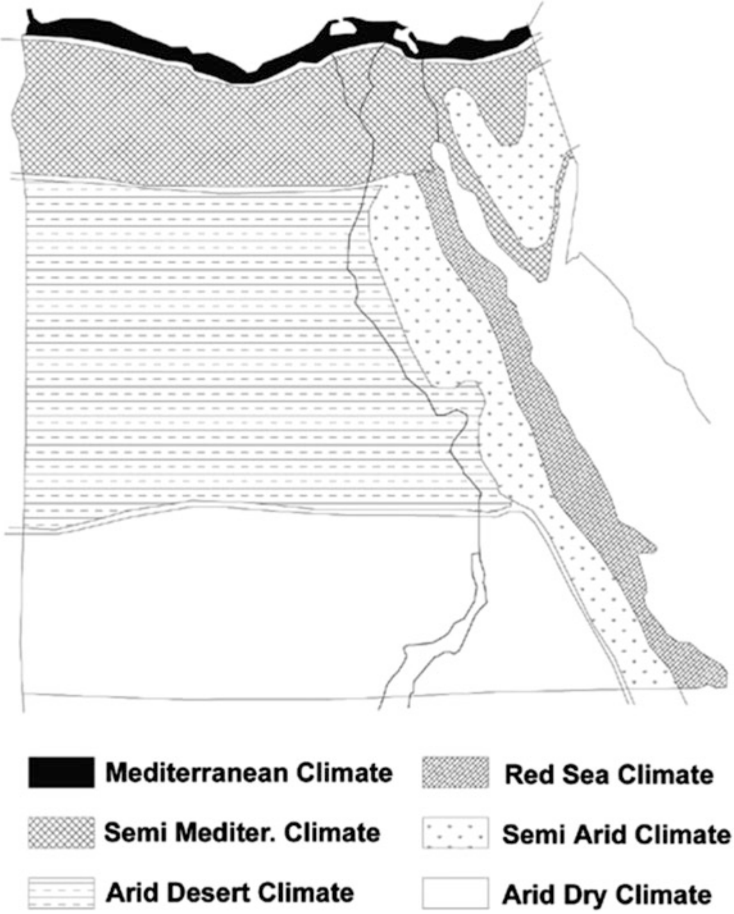


Fig. 1 Climatic zones of Egypt according to the Egyptian Organization for Energy Planning [1]

In the winter, upper winds are similar to surface winds up to a height of 1,000 m but tend to increase about 700 m aboveground to 32 km/h. Above 1,000 m, winds become northwesterly (originating in the northwest), ultimately becoming westerly (originating from the west) above 2,500 m [3].

In the summer, winds are mainly northerly (originating from the north) up to an altitude of 900 m. Above an altitude of 900 m, they tend to change direction, becoming northwesterly (originating in the northwest), at 1,800 m continuing to change into westerly and southwesterly above 3,000 m. This shows how difficult it is to predict the movement of evaporated water from the Aswan High Dam Reservoir.

The data reported by Elba [5] and shown in Fig. 4 show average wind speeds of 3.51–3.62 m/s at heights of 2–4 m above the AHD Reservoir as recorded between 1997 and 2010. Peak winds of 6.3 m/s were recorded in October 2003 while the lowest value of 1.14 m/s was recorded in December 2008. July typically has the lowest wind speed of 3 m/s while October records the maximum wind speed of 4 m/s (Figs. 2, 3, and 4) [5].

During the flood season, the winds tend to be calm in the early hours of the morning, but the speed picks up by midmorning to 10–15 m/s and blows as northeast parallel to the main axis of the water body of Lake Nasser-Nubia [3].

2.2 *Relative Humidity, Precipitation, and Cloud Formation*

Relative humidity is important to extract evaporated water from fog and dew. Carney [6] discussed the formation of dew prior to the construction of the AHD Reservoir in 1894. He noticed that the air at night was four grains heavier at night than during the day at Aswan. The curves at 8 a.m. and 10 a.m. showed an increase of absolute humidity as the air warmed up. In fields in Luxor, absolute humidity tended to drop after 8 p.m. as dew is deposited. At the Mena House Hotel in Luxor, the dew point was not reached till after midnight with 6 a.m. the point of lowest humidity in the air.

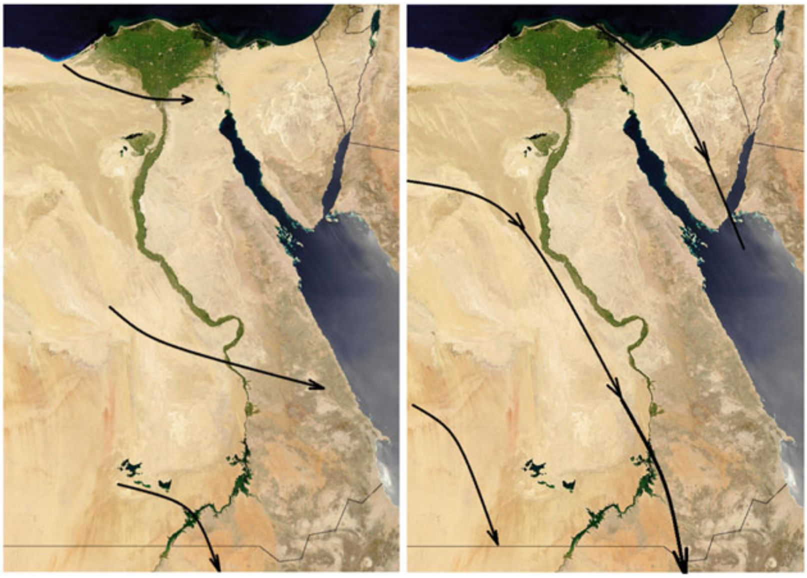
The average relative humidity for Egypt is plotted in Fig. 5.

The dew point is the temperature at which water vapor in air at constant barometric pressure condenses at the same rate as it evaporates. Below the dew point, condensation exceeds evaporation. NCAR [3] estimates that during the summer months, over the AHDR, there is no dew point until an altitude is reached where the temperature of the air is below −4°C.

Despite the high evaporation at the Aswan High Dam Reservoir, relative humidity remains very low at Aswan. This is due to the arid climate but is also a sign that water losses by evaporation move to high sky altitudes and would be more suitable for rain harvest.

Elba [5] presents relative humidity at 2 and 4 m above ground level at Aswan as well as at Toshka. Toshka has a higher relative humidity than Aswan.

At Wadi Halfa that is now submerged under Lake Nubia, the relative humidity used to be 20% in the summer and 42% in the winter.



(a) Mean Surface flow – January

(b) Mean Surface flow - April

(c) Mean Surface flow - July

(d) Mean surface flow - October

Fig. 2 Mean surface flow of winds over Egypt throughout the year, (**a**) January, (**b**) April, (**c**) July, and (**d**) October – Simplification after [3]

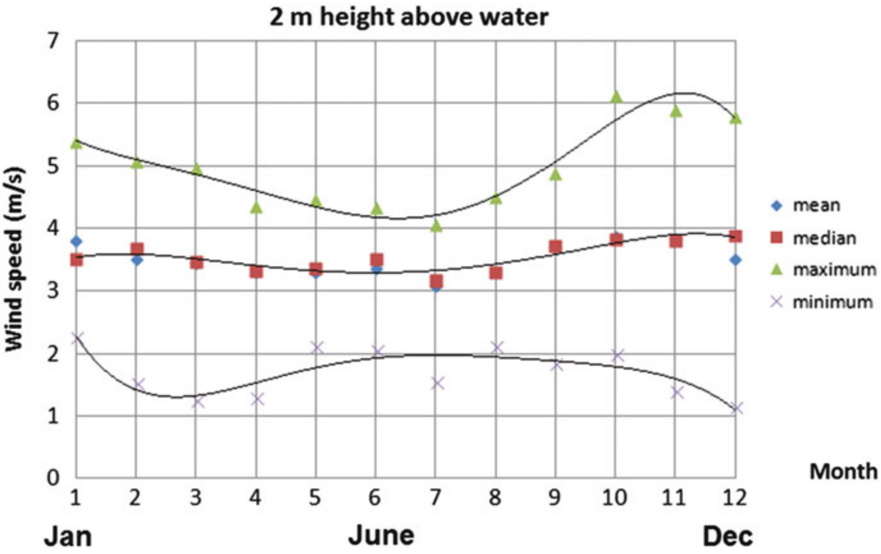


Fig. 3 Wind speed on AHD Reservoir at 2 m height after Elba [5]

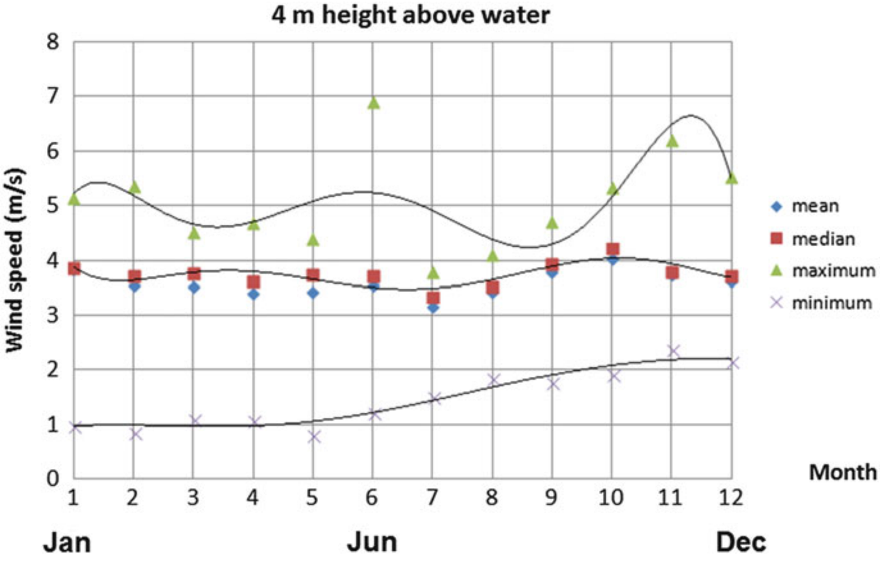


Fig. 4 Wind speed on AHD Reservoir at 4 m height after Elba [5]

Weather modification is based on trapping the clouds. Rain precipitation in the Mediterranean climate ranges between 20 and 200 mm/year winter rainfalls. The cloudy season at Alexandria occurs between October 22 and April 21. Most of the

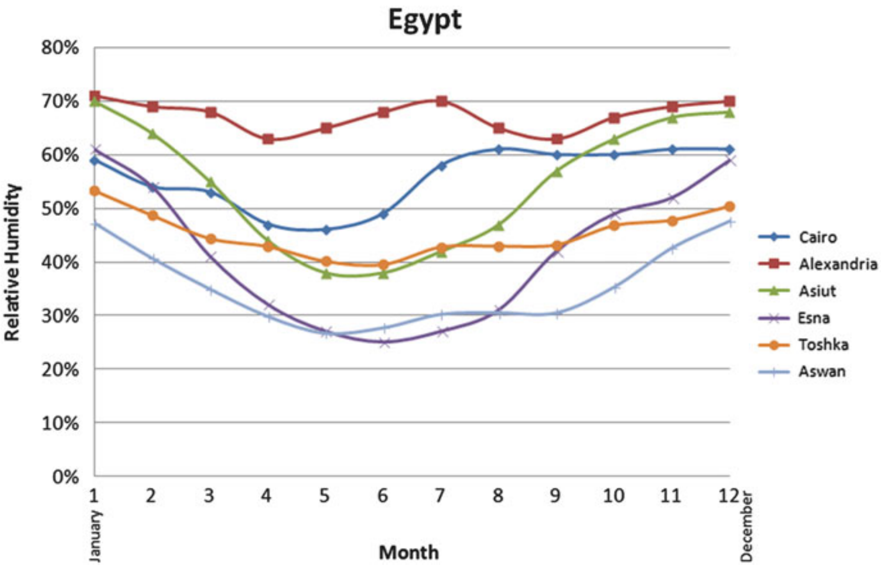


Fig. 5 Relative humidity for Egypt on a monthly basis – composite curves after www.weatherspark.com

rain falls as showers, but continuous rain is experienced from time to time. The north coast represents the area of Egypt most subject to rain precipitation.

Rain precipitation also occurs in the Gebel Elba area in the southwestern corner of Egypt and northeastern region of Sudan by the Red Sea or in the Halayeb area. Egypt established a national park over 36,000 km^2 in the Gebel Elba area. The average rain precipitation is 50 mm but can reach 400 mm/year on the peak at 1,437 m above sea level, creating a mist oasis in which most of the humidity is mist and dew.

The Eastern Desert is dry. The peak is at Gebel Shayib el Banat (2,187 m) which is surrounded by a number of high mountains creating mist oases. Rain precipitation is at 50 mm/year. Torrential rain streams through canyons called wadis.

The Sinai Peninsula offers two different climatic zones. The South is rich with mountains and wadis. The peak elevation is at Gebel Katherina (2,541 m). While average precipitation is at 62 mm/year, it occasionally rises to 300 mm/year on the peaks of mountains, falling as snow in the winter. It is the only area of Egypt where it snows.

The Gebel Uweinat in southwest Egypt is extremely dry, and rain falls once every 10 years.

An old Egyptian myth states that the sun god Ra at Esna was prevented by his arch enemy the snake Apophis from its morning rise by placing black stratus clouds that often stripe the horizon at sunset [7]. According to Quantick [8], the formation of low stratus clouds at night is a common occurrence in the summer. Its base is frequently 600 m or lowers in the Delta, and at Cairo International Airport, it may be on the surface. It tends to form on successive mornings for a period of 3–5 days but tends to disappear within 3 h of sunrise. In the winter, low stratus cloud is rare, but stratocumulus cloud based about 350 m or above may occur in the mornings.

Data collected by the World Meteorological Organization shows very limited rain at Aswan between February and April 2016 below 0.2 mm but practically nonexistent at Wadi Halfa.

Publications presented before the construction of the Aswan High Dam [3] implied no cloud formation, but recent data tend to show limited overcast (see Fig. 6). The formation of clouds can be compared against the data for evaporation from the AHD Reservoir.

In Aswan, the sky is overcast at 10–16% between January and April (Fig. 6). The clearest day with 4% overcast occurs on June 17. The clearest season begins on May 14 and ends around July 10. The sky is 15% overcast by the end of July. The sky overcast shrinks to negligible values by the end of September and starts to peak reaching a maximum of 25% on December 13. These parameters are important in planning weather modification.

The situation is different at Abu Simbel Airport, where the clearest part of the year starts around September 1 at 18% overcast and lasts until the end of November (Fig. 7). October 5th is considered the day with the most clear sky with only 8% overcast. The cloudier part of the year starts around November 21 and lasts for 9 months till September 1. The cloudiest day occurs on August 2, with 27% overcast.

There is no direct correlation between the evaporations of water from the AHD Reservoir suggesting that important losses drift with the winds; however, at the peak of the flood in August, the sky is overcast at one of its maximum values in both Aswan and definitely at Abu Simbel.

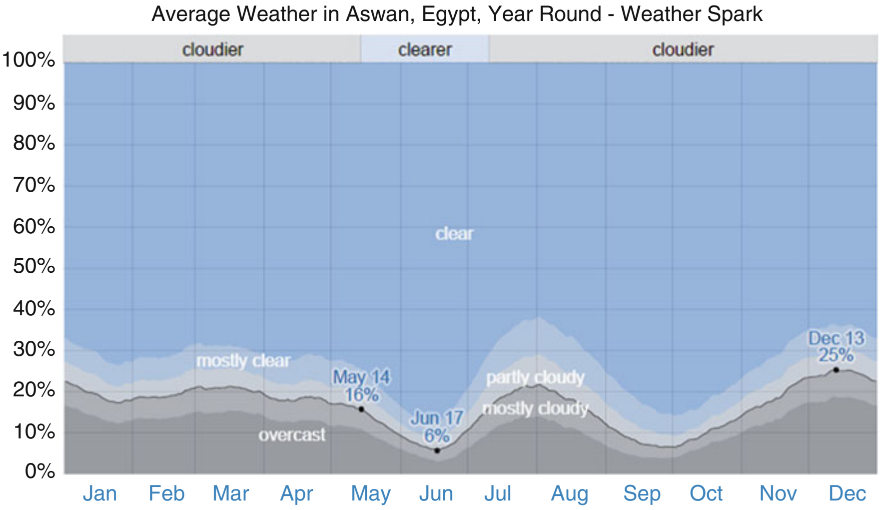


Fig. 6 Formation of clouds over Aswan throughout the year (Reproduced with permission from www.weatherspark.com)

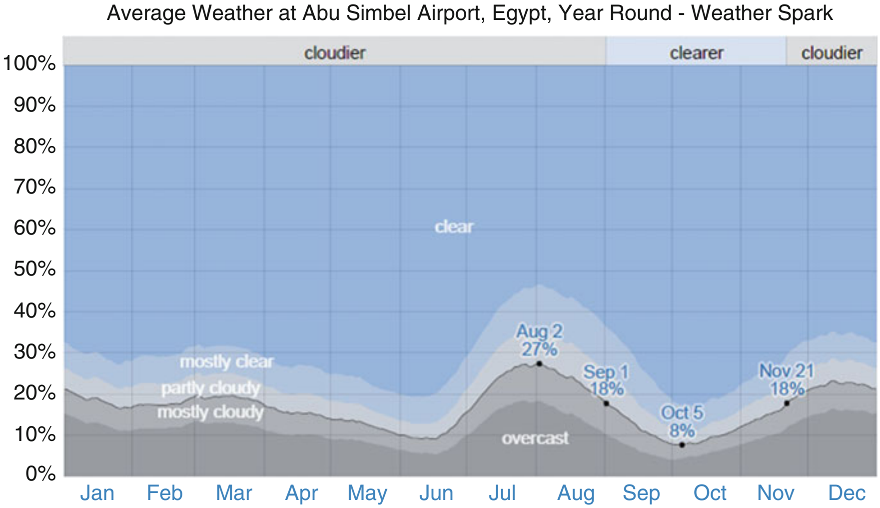


Fig. 7 Formation of clouds over Abu Simbel throughout the year (Reproduced with permission from www.weatherspark.com)

While cloud formation is at a peak in July and August over the AHD Reservoir, it is practically nonexistent in the summer over Cairo. This means that cloud seeding aircrafts could be used in different parts of Egypt at different months to maximize use of airplanes and return on investment.

3 Evaporation Losses from the ASWAN High Dam Reservoir

Egypt's demand for water for agricultural, industrial, and municipal sectors exceeded 79 km^3 in 2010 [5, 9] (industrial 2 km^3, domestic 9 km^3, agriculture 67 km^3). With a rapidly expanding population projected to reach 135 m by the year 2100, Egypt is facing an important shortage of water.

Elba [5] reported daily evaporation rates at a number of meteorological stations on the AHD Reservoir such as the Aswan station between 1995 and 2009, El-Alaky from 1999 to 2007, Abu Simbel from 1995 to 2007, Kalabsha from 2004 to 2008, Amada from 2004 to 2008, and Toshka from 2004 to 2008. The highest evaporation rates were recorded at the Amada station. The mean evaporation rate was calculated to be 7.4 mm/day, but the most frequent was 6 mm/day. The highest evaporation rate was recorded in August 2001 at 14.5 mm/day and the lowest in December 2008 at 1.9 mm/day. Compared to Amada station, the mean evaporation rate was less than 25% at El-Alaky station, 4% at Abu Simbel, 9% at Kalabsha, 13% at Aswan, and 31% at Toshka (Tables 1 and 2) (Fig. 8).

Table 1 Evaporation rates at the AHD Reservoir, after Elba [5]

Evaporation rate mm/day					
Month		Mean	Median	Maximum	Minimum
January	1	4.94	5.13	7.79	2.64
February	2	4.87	5.01	7.86	2.5
March	3	5.41	5.38	7	3.05
April	4	6.33	6.34	10.13	3.83
May	5	7.38	7.36	11.37	4.15
June	6	8.89	9.23	12.99	5.04
July	7	9.05	9.51	12.79	4.12
August	8	9.91	9.9	14.46	6.29
September	9	9.5	9.63	13.66	6
October	10	8.65	8.49	12.57	3.87
November	11	6.91	6.83	11.25	2.93
December	12	5.48	5.44	7.39	1.97

Table 2 Local evaporation rates at the AHD Reservoir, after Elba [5]

Evaporation rate mm/day					
	Period	Mean	Median	Maximum	Minimum
Abu Simbel	1990s	7.46	7.06	13.4	4.12
	2000s	8.52	7.9	14.46	3.9
	Mean	8.1	7.44	14.46	3.9
Aswan	1990s	6.96	7.12	11.89	4.29
	2000s	7.29	6.78	11.4	2.23
	Mean	7.29	6.93	11.89	2.23
El-Alaky	1990s	5.64	5.95	7.46	3.84
	2000s	6.59	6.06	12.52	2.5
	Mean	6.28	6.03	12.52	2.5
Kalabsha	2000s	7.73	8.05	11.69	1.97
Amada	2000s	8.5	8.1	12.79	2.88
Toshka	2000s	6.03	6.46	8.54	3.79

According to the world database on reservoirs, the surface area of the AHD Reservoir is 6,000 km^2 [12].

Multiplying the average evaporation rate of 7.4 mm/day for 365 days over a surface area of 6,000 km^2 gives

0.0074 m/day $\times$ 365 days $\times 6000 \times 10^6 = 16{,}206{,}000{,}000$ m^3 of water losses, or 16 billion cubic meters of losses

Based on the estimated annual consumption of water of 79 km^3 for municipal, agricultural, and industrial applications, the annual evaporation represents a 20.5% loss that should be recuperated by rain harvesting. It is also a loss of 10% of the storage capacity of the reservoir.

This calculation can be compared with published data.

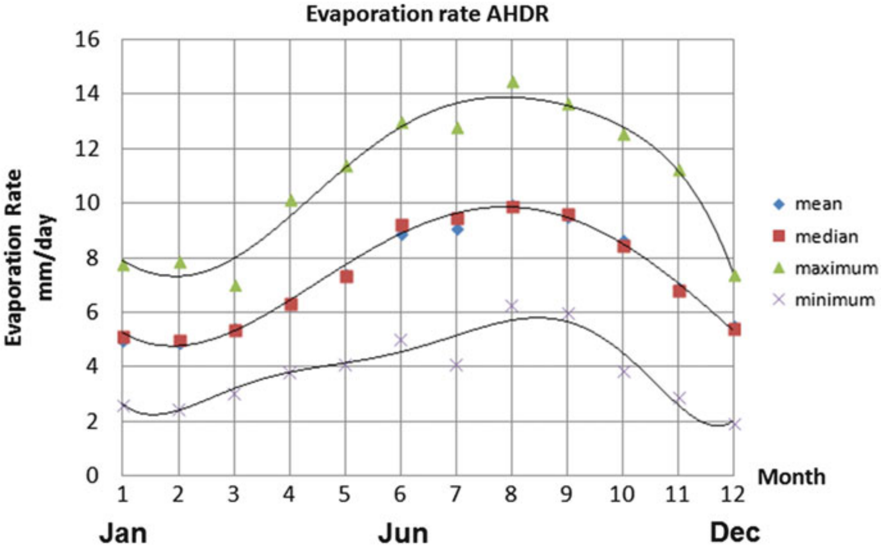


Fig. 8 Evaporation on a monthly basis, after Elba [10, 11]

Elba et al. [10] estimated evaporation losses at 2,700 mm/year and calculated an average loss of 15 billion cubic meters per year. They recommended drying some khours to reduce evaporation losses by 10%.

Ebaid and Ismail [13] measured evaporation losses to be between 2.4 and 9.58 mm/day for the month of March; they estimated that the loss was of the order of 0.86 billion cubic meters and recommended to dry out a couple of khours to reduce evaporation losses and save 2.4 billion cubic meters per year. They also concluded from their calculations that the evaporation losses were in the range of 10–16 billion cubic meters per year.

Hamdan and Zaki [14] estimated losses by evaporation to vary between 12 billion cubic meters for the years 1995/1996 and 15.5 billion cubic meters for the years 2007/2008. They calculated that the ratio of losses by evaporation to inflow for storage was between 3.55 and 20.26% on an annual basis and averaged 12.65%.

Sadek et al. [15] estimated average evaporation losses to be between 4.65 and 7.95 mm/day.

Omar and EL Bakry [16] estimated the evaporation losses over the AHD Reservoir to average 14 billion cubic meters per year (14×10^9 m^3).

Elba et al. [11] estimated that evaporation losses will increase by 3–10% due to climate change, as well due to the reduction of reservoir depth through siltation. They calculated that annual evaporation losses could climb to 20 billion cubic meters (20×10^9 m^3) of water.

McCully [17] estimated that the average evaporation of water is 11.2 km^3 of water. This is equivalent to 10% of the water being stored in the AHD Reservoir, but his estimate is not derived from the data collected more recently by Elba et al.

Table 3 Average daily evaporation volumes of water over AHD Reservoir calculated after [5, 10, 11]

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
29.64	29.22	32.46	37.98	44.28	53.34	54.3	59.46	57	51.9	41.46	32.88

[10] at 15 km^3 of water. Elba et al. [10] also predicted an increase of evaporation by 3% to 10% by the year 2100 due to deterioration of climate.

Hassan [18] conducted an estimate of evaporation data from remote sensing by different calculation methods. The average evaporation rate ranged from 6.2 to 9.5 mm/m^2/day.

Based on the available information, schemes of weather modification would have to be designed to compensate for the loss of 30 and 60 million cubic meters of water per day, peaking in August, a very hot month at the time of Nile flooding (see Table 3 and Fig. 9).

An important factor when evaluating evaporation rate is the actual surface-area-to-volume (SAV) ratio. The more the reservoir siltsup the smaller SAV becomes.

A number of scholars have discussed the impact of the GERD. Conniff [19] estimated that during the construction of the GERD, the flow of water to Egypt will be cut by 25%, based on a study by the American Journal GSA Today. The study was led by the Smithsonian Institution and the geologist Jean-Daniel Stanley who predicted that Egypt will face very serious water shortage by the year 2025.

Nashar and Elyamany [43] reviewed previous studies on water losses from the construction of the GERD.

- Evaporation losses risk to increase by 5.9% over the AHDR.
- Water supplied to Egypt could drop by 5–15% and Nile water levels could decrease by 0.4–0.75 m.
- Surface area of agricultural land in Upper Egypt could decrease by 29.7%.
- Surface area of agricultural land in Lower Egypt could decrease by 23.03%.
- Hydropower from the AHDR could decrease by 20–30%.

With the water level in the AHD expected to drop for an average depth of 110 m, due to the construction of the Grand Ethiopian Renaissance Dam (GERD), a lower SAV is anticipated. The SAV is however not uniform across the AHD Reservoir as a result of advanced sedimentation in Lake Nubia leading to a highly depleted volume of water.

4 Fog and Mist Harvesting

One of the consequences of establishing water reservoirs is the increase of fog in the winter by the passage of cold air over warmer water in the reservoir [20]. Nemec [4] views the increase of fog as a form of thermal pollution from the man-made reservoir, but in a country, as arid as Egypt, it should be viewed as a gift from nature of potable water.

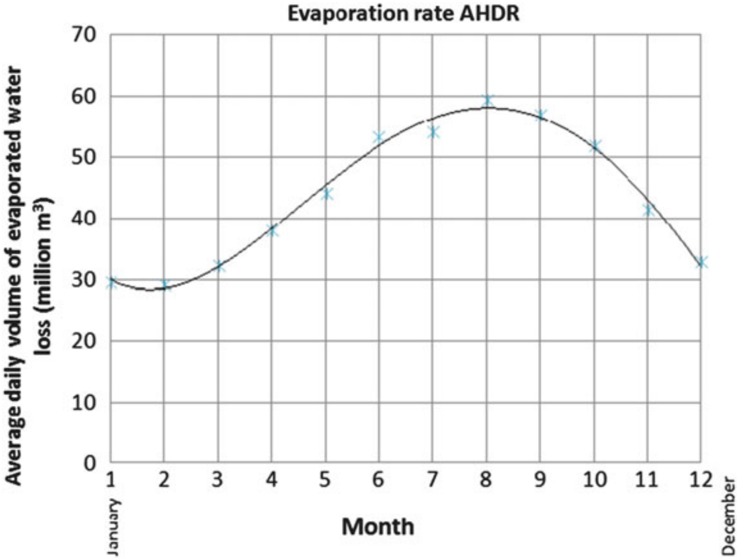


Fig. 9 Average daily evaporation from the Aswan High Dam Reservoir after Elba [5]

Fog consists of water vapor just above the Earth that condenses into small droplets when it comes in contact with objects.

Archeologists have found evidence that the Ancient Egyptians built piles of stones in such a structure that fog condensation would trickle down the inside walls to be collected and stored (Cho [21]).

Fog can be noticed throughout Egypt in the winter months even in arid areas in the first hours of the day. Morning fog is common in Lower Egypt and along the Aswan High Dam Reservoir [22]. Heavy fog was reported in Cairo in January 2017 due to high humidity coinciding with low wind speed [23].

There are different categories of fog:

Advection fog – cooling of air occurs to its saturation point when it moves as warm air but comes in contact with a cooler surface to the point of reaching the dew point to cause fog.

Evaporation (mixing) fog – it forms when warm air moves over a cold water surface. As water is warmer than surrounding unsaturated cool air, it causes mixing of water vapor droplets to the point of saturating the moving air, causing fog.

Radiation fog – Air cools at ground level to the point of forming a local cloud. The cooling occurs at night by radiation to the black sky forming fog.

Upslope fog – fog forms as moist air moves to the top of a hill or a mountain; it tends to expand and become cooler. If there is sufficient moisture in the air, fog forms as the air cools down.

Valley fog – it occurs as cooler air moves down the slope of valleys, and it is often associated with radiative cooling. Several hours after sunset, mountain wind pushes moist air down the valley causing the formation of fog.

The terms fog oasis and mist oasis are interchanged. These oases form at sufficient altitudes when fog precipitates to allow growth of seasonal vegetation [24].

Fog only lasts for few hours. The mean velocity is very low; Cotton et al. [25] suggest assuming an updraft of 0.01 m/s. The liquid content of fog is in the range of 0.05–0.2 g/m^3.

Although the data on the movement of evaporated water from the AHD Reservoir is lacking, the conditions would favor formation of fog at high altitudes of the Eastern Desert and Upper Nubia. The Atacama Desert in Chile, the Western Sahara, and the desert of Baja California are coastal deserts where the only source of water is fog.

According to the Organization of American States [26], fogs occur frequently in Peru and Chile along coastal areas at high altitude and are called “camanchacas.”

Egypt has a similar phenomenon on the peaks of mountains of the Eastern Desert and the Sinai Peninsula forming “mist oases.”

Fog harvesting represents an innovative technology easy to adapt for Egypt. It is particularly promising as it would produce drinking water for remote communities, free of the very damaging disease of bilharzias, also known as schistosomiasis. According to the UNISA [27], potable water collected by fog harvesting in South Africa meets the standards of the World Health Organization.

Fog collectors are more effective when installed at coastal areas or near large lakes as the fog moves inland driven by the wind. Sharan [28] points out that fog harvesting is more efficient near the ground (not above roofs) in valleys. Fog can also be caught at high altitudes of 400–1,200 m above sea level when water is present in stratocumulus clouds.

Fog collectors have been installed successfully in Chile, Peru, Mexico, and Ecuador, [26]. The fog collector typically uses a flat rectangular collector 2 m wide and 24 m long, with a surface area of 48 m^2. A number of collectors can be installed in series.

The surface of the fog collector consists of a fine mesh of nylon or polypropylene. In Chile, a shade cloth called Raschel made of black polypropylene filaments 1 mm wide × 0.1 mm thick in a triangular wave is used. Numerous tests were conducted in a pilot plant at El Tofo in Chile. The most optimum collector provided 35% surface interception in double layers. This proportion of propylene-surface-to-opening extracts 30% of the water from the fog passing through the nets [26].

The tests were conducted between 1967 and 1988 and involved a number of Chilean academic institutions such as the National Forestry Corporation, the Catholic University of the North, and the Catholic University of Chile in different regions at altitudes between 530 and 948 m. The technology proved that good-quality potable water could be produced for commercial, industrial, and agricultural use [26].

In Peru, a number of academic institutions have tested the technology since the 1960s such as the National Meteorological and Hydrological Service (SENMHI) in collaboration with the Estratus Company in a number of regions such as Lachay, Pasamayo, Cerro Campana, Atiquipa, Cerro Orara (Ventinilla-Ancón), Cerro Colorado (Villa María del Triunfo), and Cahuide Recreational Park. OAS [26] also mentions the southern Ecuador Center for Alternative Social Research (CISA) that started implementing the Chilean model in the National Park of Machalila on Cerro La Gotera.

The efficiency of fog collectors was discussed by Schemenauer and Joe [29] to harvest the fog from the camanchacas for large fog collectors in Chile. The camanchaca exhibited characteristics of clouds sourced from marine stratocumulus. The mean volume diameter (MVD) of droplets ranged between 10.8 and 15.2 μm in ten cases. Droplet concentration was 400 droplets/cm^3 with fog liquid water contents ranging from 0.22 to 0.73 g/m^3. The authors stated that the theoretical efficiency for a 1-mm-wide polypropylene ribbon for fog droplets in the stated range of MVD of droplets was supposed to be from 75 to 95% at the wind speeds ranging from 2 to 8 m/s. Field data indicated that the efficiency could drop to 20% compared to data measured 6 m upstream of the collector. The large collectors are believed to slow down the wind causing a drop of collection efficiency.

More pilot projects have been conducted in the last decade (Table 4) near the Red Sea in Yemen and Eritrea according to UNISA and in India [30], Ghana [31].

While Eritrea achieved 8 L/day/m^2, Yemen achieved 113 L/day/m^2.

Morocco was reported to have built the largest fog harvester in the world at Dar Sidi Hamad [32]. The fog harvester supplies water to a small community of 400 people in the desert at the rate of 88 L/day/m^2. These numbers are not in concurrence with those of Lekouch et al. [33], who report typical values of 10–15 L/m^2/day (Fig. 10).

Whereas most fog collectors are flat rectangular standing in the wind, Ethiopia has developed an interesting concept called the Warkawater Tower. It is 10 m tall with a diameter of 4 m. They are called after a very tall tree, the Warkawater, which rises to 25 m heights; the Warkawater towers were designed by Arturo Vittori to catch both fog and dew [34].

Once installed, the fog collectors do not need the energy to operate as the water vapor is transported by the wind. Based on data collected in the 2000s, fog collectors cost between \$25/m^2 and \$35/m^2 and last 10 years with low maintenance. These prices are based on importing the collectors from Chile and may be reduced by developing the technology in Egypt as there is a strong infrastructure for the manufacture of plastics and metal fabrication.

To increase the efficiency of fog capture, the Massachusetts Institute of Technology (MIT) has partnered with Chilean engineers to develop low-cost mesh fabrics [35]. The research at MIT [36] focused on the ability of materials for the

Table 4 Water collection from fog collectors [27]

Project	Total surface area (m^2)	Water collected (liters/day)
University of South Africa	70	3,800
Yemen	40	4,500
Cape Verde	200	4,000
Dominican Republic	40	4,000
Eritrea	1,600	12,000

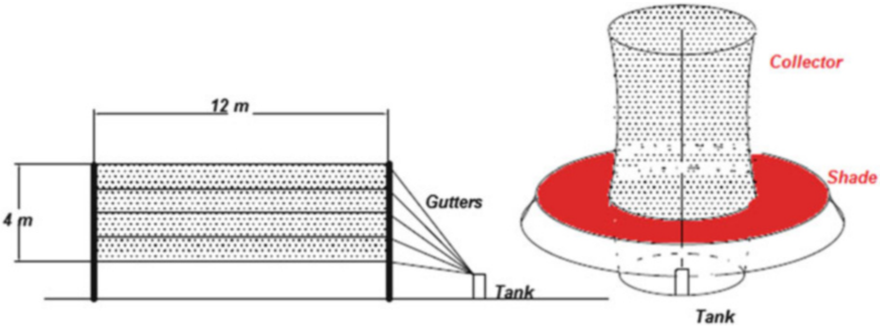


Fig. 10 Conventional flat vs. tower fog collectors (simplification by author)

mesh to absorb or repel water as well as the surface texture of the mesh (e.g., incorporating bumps).

Once the water is collected in the collector, it is allowed to run down by gravity through gutters to a storage drum or tank or into a canal for irrigation [37].

The tower collector is an interesting innovation by Italian and Ethiopian engineers (see Fig. 10). If the mesh is all around the tower, it forms a double-stage process with two capture surfaces. It can also accept the wind that transports the fog droplets from different directions throughout the year. The shade cover protects collected water from further evaporation. The cylindrical configuration would resist sandstorms better than a flat collector exposed to the “khamsin” in Egypt.

No data is available to determine the amount of water evaporated at the AHD Reservoir that converts into the fog. Further studies are required.

5 Dew Harvesting and Nocturnal Radiation

Fog formation is associated with air reaching the dew point to cause moisture capture. Scientists have therefore attempted to cool down air by flowing it between a film and a plate to reach the dew point. This concept is called dew collection.

Dew occurs when atmospheric vapor condenses on a body that has been cooled by radiative cooling at night.

In the lower layers of the sky, most arid areas of Egypt experience a large inversion of temperature at night due to nocturnal radiation of the ground losing heat to the black sky. Nocturnal cooling of Egypt was studied by a French nobleman in the nineteenth century, Lucien de La Rive, who reported nocturnal cooling down to 0.4°C on the bank of the Nile, as reported by Marcet [38]. This loss of heat is not effective in large cities such as Cairo where light pollution at night from homes and infrastructures diminishes the potential for nocturnal radiation.

Similar ideas were used in the past. The Ancient Egyptians invented nocturnal refrigeration [39, 40]. The sky of Egypt acted as a black body absorbing heat by radiation at night causing nocturnal cooling. The Ancient Egyptians placed water in shallow pottery that cooled down forming a very thin layer of ice. The ice was collected in the morning, put in jars, and used to preserve food. This knowledge was further advanced by the Ancient Persians who developed very large nocturnal refrigeration systems with special wind barriers facing predominant winds on the Iranian Plateau. This knowledge has been lost in Egypt in modern times. Therefore, in an Egyptian concept, loss of heat during the night by nocturnal refrigeration is a concept that can be applied to enhance dew harvesting.

Abulnaga [39] conducted a study on the potential for nocturnal refrigeration for preserving food in certain regions of the Sahara for the Ministry of Agriculture of Senegal under the sponsorship of the United Nations University. Abulnaga [39] proposed the construction of low-cost collectors with a gray paint to enhance radiation to the sky, based on the success of French scientist to desalinate brackish water in the Atacama Desert by nocturnal refrigeration.

The inversions of temperature disappear in the morning when temperature decrease with altitude may exceed adiabatic lapse rate for dry air. According to the National Center for Atmospheric Research, the inversion of temperature is associated with vigorous vertical currents that may exceed 2,500–3,000 m; to 4,000 m above sea level.

Sharan et al. [41] proposed a suitable white low-density polyethylene film containing microparticles with high infrared emissivity. These particles are typically mixed titanium dioxide and barium sulfate. The film is passed on a thermally insulated material and cools below the dew point temperature of the air through loss to the sky by radiation.

A large dew collector was built in the Kutch area (Gujarat) of India to provide clean potable water for a mining project [41]. The collector collected 0.566 mm/night over a period of 192 days. The authors claim that it was the largest ever built with a total surface area of 850 m^2. It consisted of trapezoidal ten ridges and trough modules 33 m long and 0.5 m wide at the top and 2.2 m wide at the base and sloping at 30° from the horizontal. The project was financed by the World Bank. The cost of potable water from these collectors was 0.074 US$/L in a country where bottled water averaged 0.22 US$/L.

Lekouch et al. [33] conducted a study on dew, fog, and rain collection in Southwest Morocco. The study used 1 and 2 m^2 collectors. The collectors were covered with a foil made of low-density polyethylene impregnated with infrared emitting materials of titanium oxide and barium sulfate. A non-soluble surfactant is applied to render the surface more hydrophilic. The film is insulated in the back, and the collector is set at an orientation of 30° with respect to the horizontal, to lose heat by nocturnal radiation. The collectors were set facing north, east, south, and west during the test period. Water condensing from the atmospheric air was collected by gravity. This extensive study showed that dew could be collected in different areas of Morocco at rates as low as 0.3 L/m^2/year at Ouarzazate and as high as 18.1 L/m^2/year at Agadir. The collection was compared to the average annual rain of 43 mm/year at Agadir and showed that potable water collected from dew collectors was lower in cost than spring water extraction after filtration and bottling.

Table 5 Potential of fog harvesting in Egypt (Comparison by author)

Features and advantages	Potential challenges and disadvantages
Large quantities of fog result from evaporation at the AHD reservoir to be confirmed	Data on fog is missing and must be collected, and pilot projects must be established
Potential for collection in the valleys and canyons or wadis in the Eastern Desert or on top of the mountains of the Red Sea and Sinai coasts	These areas are not habited, and water could be wasted if not well managed
Good potential along Mediterranean climate zones (north coast, North Sinai) or coastal deserts of Egypt	Infrastructure to collect water is often limited and would require the installation of tanks or fill in old wells
Potable water meets World Health Organization standards	If poorly maintained, water quality would deteriorate
Water would be free of bilharzia	Flies or insects caught in mesh could lay larvae eggs
Collectors can be manufactured in Egypt	Training must be provided
Fog is limited to few hours in the morning in the Northern Delta or Cairo area	Large storage would be needed for potable water use, or the collected water would have to be channeled back to existing irrigation canals where it cannot be stored, losing the potential for precious potable water
"Zabaa," lofty whirlwind that occurs occasionally	Must design collectors that can be folded away or resist the whirlwind, such as tower collectors instead of flat collectors
Khamsin sandstorms	Occur between March and June – collectors must be folded away or designed to resist the sandstorm

The study identified four parameters that influence dew collection, air temperature, dew point, wind speed, and cloud cover. Cloud cover at night tends to reduce nocturnal radiation and slow down dew recovery.

A nonprofit organization OPUR [42] – International Organization for Dew Utilization – based in France disseminates information of water harvesting from dew and fog.

Regarding the dearth on data for fog harvesting in an Egyptian context, there are merits and challenges to test the technology as proposed by Table 5. Suitable collectors can be manufactured if designed to resist the harsh environment of annual sandstorms, but could become a source for potable water in isolated communities of the coastal deserts.

6 Weather Modification

The Nile faces numerous challenges [19, 43]. While Ethiopia embarks in the construction of the GERD, Egyptian politicians are struggling to recover from the loss of water as a consequence of this new massive project at the source of the Nile.

Fig. 11 Accumulation of clouds at the equator by movement of clouds from the northern and southern latitudes, photo reproduced from NASA (www.nasa.gov)

Discussions drag on agreements signed at a time of British colonialism to no avail. These discussions do not cover the water losses by evaporation over the AHD Reservoir, that are of the order of 11–16 billion cubic meters (Elba et al. [10], Ebaid and Ismail [13], Hamdan and Zaki [14] Omar and El-Bakry [16]). These losses are transported by wind, migrating south toward the equator south and southwest, feeding the sources of both the Blue Nile and the White Nile (Fig. 11).

The Sahara, including most of South Egypt, is in a zone of influence of the Hadley cell. Air rises over the equator to the height of 10–15 km losing moisture by rain precipitation as the air cools down. Dry air moves toward the pole and then descends back turning back toward the Tropics of Cancer and Capricorn at 30 north and south latitudes, causing high-pressure zones on deserts and oceans, picking up moisture as trade winds back to the equator. These winds curve as a result of the Coriolis forces due to the rotation of the Earth. Aswan at latitude of 24° north lies very close to the Tropic of Cancer at 23°27N. Near the sun at the time of the solstice, the sun is 90° above the horizon. Cairo is at latitude of 30.044 N. This

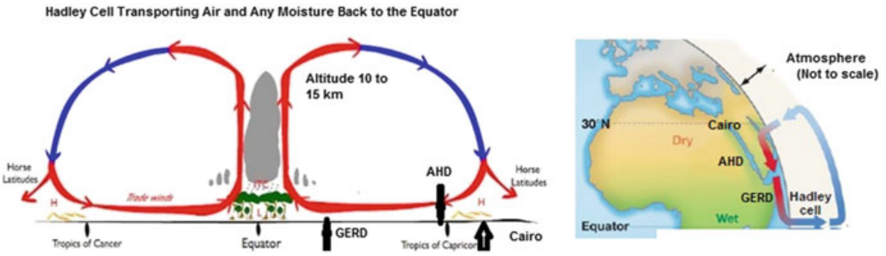


Fig. 12 The Hadley cell forces Egypt and Sudan to feed the GERD by sending back the evaporation losses from the AHD Reservoir toward the tropics (Simplification by the author). The construction of the AHDR changed evaporation patterns as it has been experienced with large reservoirs [44]

means that the entire Upper Egypt falls in the zone where the air flows back toward the equator (see Fig. 12).

The construction of the AHDR changed evaporation patterns as it has been experienced with large reservoirs [44]. The potential to capture the moisture due to water evaporation over the AHD Reservoir should start from Aswan, south towards the border of Sudan and towards the Red Sea). Certain authors such as Borushko I.S. [44] have documented the change to humidity near large man made reservoirs. When the area of the AHD Reservoir is superimposed on the map of mineral resources of Egypt and Sudan [45], opportunities appear, which justify the cost of weather modification for a boom in the mining industry.

Cloud seeding or rain enhancement was developed in 1946 by the Desert Research Center, in Reno, Nevada, USA. Substances such as crystals of silver iodide are spread coalescing water droplets into clouds and precipitation. Over the last 70 years, it has become a tool for replenishing water reservoirs for hydroelectric dams, combating drought in numerous arid and semiarid parts of the USA. The cost of additional rain created by weather modification is of the order of US\$15/acre-foot or \$0.012/m^3. In 2016 cloud seeding was practiced over 28 million acres in Texas but has been extended over 61 million acres in periods of drought. The area is many folds as large as the total farm area of Egypt estimated at 7.2 million acres.

Cloud seeding requires special conditions such as the correct size of water droplets, temperature, and humidity. Not every cloud can be precipitated into rain by spraying a chemical such as silver iodine, aluminum oxide, or barium. Certain companies favor airships [46] over airplanes [47]. Other scientists have experimented with lower-cost drones in Nevada [48]. The WMO [49] questioned the impact of silver iodine on cloud seeding.

Egypt and Sudan do not have currently a program for weather modification or cloud seeding. This chapter is, therefore, an attempt to open the discussion on the merits of this technology. Unfortunately, data is unavailable to give an estimate for the efficiency of water recovery by weather modification.

The United Arab Emirates [50] is becoming the principal implementer of cloud seeding in the Middle East. The Ministry of Presidential Affairs has an ambitious program of cloud seeding, using modernly sophisticated weather radar to monitor the weather around the clouds. The project was started in 2010 at the cost of \$11 million/year and has been successful in creating rain in the desert near Abu Dhabi. Kuwait is also embarking on its own research activities to develop cloud seeding.

The WMO [51] lists new technologies and programs such as:

- SNOWIE or Seeded and Natural Orographic Wintertime clouds, in Idaho, USA
- CAIPEEX – Cloud Aerosol Interaction and Precipitation Enhancement Experiment
- SDS – dust mixed with other pollutants
- TMR aerosol-cloud-precipitation interactions
- HIWEATHER – role of aerosols, microphysical-dynamical interaction in severe weather

The experts noted that substantial funding in weather modification had been allocated between 2011 and 2016. The United Arab Emirates established a special research fund for studies in weather modifications.

The potential advantages of weather modification include:

- Increased recovery of agricultural land from deserts as enhancement to irrigation
- Increased reservoir level for the AHD in compensation for losses due to the construction of the GERD
- Recovery of water losses by evaporation from the AHD Reservoir
- Improved economic stability in periods of low Nile floods
- Slowing down the reduction of the water table due to excessive well pumping throughout Egypt
- Replenishment of the Nubian sandstone aquifer
- Creating new opportunities for wildlife sanctuaries
- Enhancing opportunities for mining communities in the Eastern Desert by providing water through cloud seeding

To assess the benefits of weather modification, Johnson [52] proposed a baseline based on an increase of 5% of the annual rainfall. This baseline concept would not apply to Egypt when rainfall is often less than 65 mm.

Weather modification should be viewed as a long-term strategy for Egypt and Northern Sudan. A number of steps must be taken to avoid failures and pitfalls experienced in the past in some arid countries:

- Better understanding of the difference between convective clouds and stratiform orographic clouds
- An understanding of the occurrence of vertical currents rising to 4,000 m and transporting evaporated water, associated with the inversion of temperature between night and day
- Proceeding with adequate knowledge
- Use of three-dimensional weather radars
- Proper project planning and coordination between different government agencies and flight contractors and end users such as farms and mines
- Continuous commitment by funding agencies and scientists
- Proper training of project scientists, leads, and managers

- Pilot projects and continuous monitoring
- An appreciation of the multifaceted nature of the project

Levin [53] proposes two main types of cloud seeding processes:

- Glaciogenic seeding – dispersing ice-producing materials in clouds at a temperature below 0°C
- Hygroscopic seeding – dispersing large hygroscopic or salt powders in a cloud, causing particles to grow quickly

The study lead by Levin showed that cloud seeding is more effective with clouds about to precipitate but fails to create new rain when the surrounding atmospheric conditions are not prone for precipitation.

A study conducted by Sharon et al. [54] and reported by Levin [53] showed that seeding cumulus clouds with glacionic material enhanced precipitation by 30% for storms that produced less than 5 mm of rainfall per day but was detrimental and ineffective on storms producing more than 15 mm of rainfall per day.

Levin reported the failure of Israeli cloud seeding when airplanes did not rise to the appropriate altitude. These failures were based on the assumption that the clouds over Cyprus and the Eastern Mediterranean Coast (Palestine, Israel, Lebanon, and Syria) were continental. These clouds are more microphysical maritime in nature.

Tests conducted in Tasmania, Australia [55], showed more success when focusing on high-altitude stratiform orographic than on convective clouds. The clouds needed to be at a temperature of −10° to 12°C.

Success with cloud static seeding of convective clouds has been limited in the past to cold conditions where the application of precipitating chemicals could enhance freezing of the water in larger particles. These conditions require the clouds to reach temperatures of −10 to −20°C. These conditions cannot be met in Egypt with low convective clouds.

Hygroscopic seeding is a new form of weather modifications pioneered by warm countries. It requires the application of chemicals and sometimes in two passes of different agents.

There are a number of factors that point out that weather modification over the AHD Reservoir and Upper Egypt should be carried at a minimum altitude of 1,500 m and preferably 4,000 m altitude. Certainly, clouds over the northern coast of Egypt are of Mediterranean origin and may need to be seeded as stratiform orographic clouds of high altitude.

The WMO lists 56 countries with three different programs of weather modification:

- Precipitation enhancement programs (Morocco, Libya, South Africa, Saudi Arabia, Emirates, Iran, Israel, Spain, Pakistan, India, Australia, Mexico, Brazil, Chile)
- Hail suppression (Canada, Germany, Argentina, Bulgaria)
- Precipitation and hail suppression (USA, Russia, China)

None of the countries of the Nile Basin, such as Egypt, Sudan, Ethiopia, Eritrea, Kenya, Uganda, Congo, and Burundi, have any weather modification programs.

Asian countries such as China are experimenting with hygroscopic seeding that allows capturing clouds at warmer temperatures. Scientific data is lacking although the process is reported to be successful.

7 Discussion

Figure 13a presents a flowchart for weather modification for Mediterranean based moisture and rain, while Fig. 13b presents a flowchart for Weather Modification to recover water evaporated from AHDR with areas marked in red show proposed weather modification, fog, and dew harvesting.

In this chapter, a number of Egyptian and international researchers were listed for having estimated the losses by evaporation over the AHDR to be between 11 and 16 billion cubic meters per year or between 3 and 20% of the inflow of water to the reservoir with an average of 11% depending on many factors, such as low and high floods, depth of water in the reservoir, presence of khours, accumulation of sediments, and siltation. Egypt has a rapidly growing population facing a shortage of water. While seawater desalination is considered by many experts, the costs remain

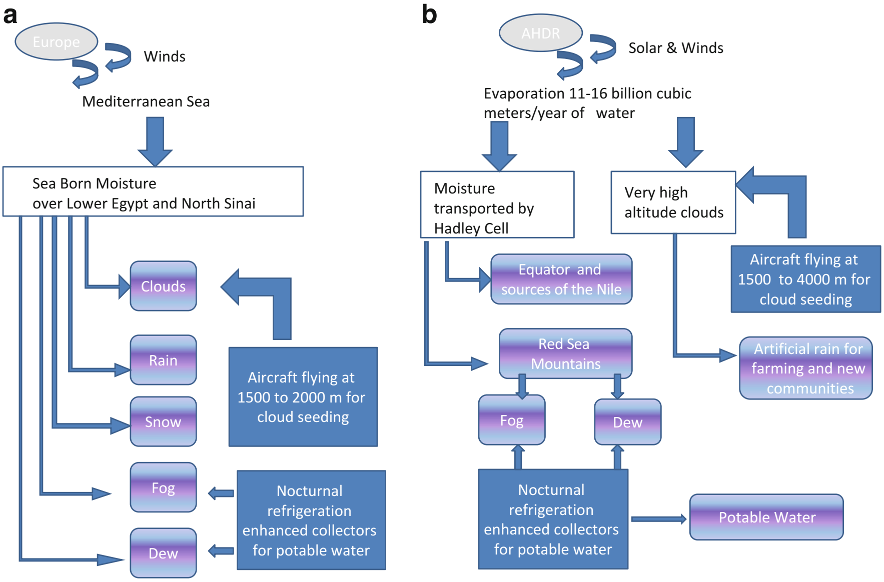


Fig. 13 Evaporation and precipitation flow chart – areas marked in red cover proposed technologies for cloud seeding, weather modification, fog harvesting, and dew harvesting. (**a**) Flow chart for weather modification for Mediterranean based moisture and rain. (**b**) Flow chart for weather modification to recover water evaporated from the AHDR

high. Its success on a large scale has depended on countries with immense wealth such as Saudi Arabia. As a result, it has often been limited to isolated touristic spots in Egypt in the form of reverse osmosis in hotels, but has not satisfied the immense needs of water in Egypt.

Researchers such as Elba et al. [10, 11] and Elbaid and Ismail [13] have suggested to dry out certain large khours to cut down evaporation by 10%. Abulnaga [56], Abulnaga and El-Sammany [57], and Abulnaga and Abdel-Fadil [58] have recommended removing sediments from bottom of the AHDR to increase storage capacity and recover the depth of the reservoir. This would also have a positive effect by modifying the actual surface-area-to-volume (SAV) ratio to reduce evaporation.

Although there are numerous successful pilot projects of fog harvesting in fog and mist oases throughout coastal deserts from Chile to Eritrea to Yemen, Ethiopia has found it necessary to innovate the tower collector with a shade to prevent further losses of collected water. A comparison of the efficiency of flat vs. tower fog collector has not been published yet, but very advanced universities such as the Massachusetts Institute of Technology are promoting new materials to enhance collection of fog in collectors. Ultimately Egyptian scientists must develop efficient collectors that can be manufactured with local materials and would be strong or flexible enough to resist sandstorms during the spring months. They can become a good source of potable water.

The Ancient Egyptians and Ancient Persians were champions of nocturnal refrigeration and dew collection well before the Rankine refrigeration cycle was ever invented. Both civilizations learned to use the black sky of the night to cool down water to form ice through nocturnal radiation. The concept of nocturnal radiation with diurnal inversion of temperature should be the basis of new dew collectors for production of potable water.

Weather modification through cloud seeding is a complex science. Many past claims of success including in neighboring Israel have turned out to be false. The clouds must be captured at a low temperature when the moisture can coalesce into large droplets. There is evidence that moisture from the Aswan High Dam Reservoir rises to 1,500–4,000 m. The science is progressing, as new products are developed in Asia for hygroscopic seeding to allow capture of clouds at warmer temperatures.

Cloud overcast is between 5 and 25% throughout the year but peaks during the flood season in July and August and in December. Moisture tends to move back to the equator through the Hadley cell. Weather modification should, therefore, focus on precipitating evaporated water losses back over the AHD Reservoir, over Upper Nubia and Lower Nubia, over the Eastern Desert mountains, and over Halayeb.

There are 56 countries listed by the World Meteorological Organization in 2016, but none of the Nile Basin. Although Egypt does not have any program, its neighbors Libya, Israel, and Saudi Arabia are active. It is hoped that this chapter encourages scientists, engineers, and decision-makers to turn their attention to the sky and air of Egypt for water, as efforts of water management should not be limited to irrigation from the Nile or deep depletion of the Nubian Aquifer. It is hoped that Egypt will develop a unique expertise in weather modification specification to the juxtaposition of one of the largest man-made reservoirs in one of the aridest zones of the world.

8 Conclusions

The science of weather modification is slowly evolving from early attempts in the middle of the last century in the USA and Australia and has gradually grown to encompass 56 countries with different schemes. Unfortunately the countries of the Nile Basin, including Egypt, have ignored this new science.

In the particular context of Egypt, various scientists have estimated the loss of water by evaporation over the Aswan High Dam Reservoir to be between 11 and 16 billion cubic meters per year. The variation depends on many factors such as fluctuation of floods, rains over the equator, siltation, and changes in the surface-area-to-volume (SAV) ratio. The construction of the Great Ethiopian Renaissance Dam (GERD) is anticipated to increase the surface-area-to-volume ratio through a decrease of water level between 0.4 and 0.75 m but also by capturing more sediment.

By the Hadley cell and the meteorology of the Sahara, water losses due to evaporation tend to move south and southwest toward the equator. Thus, these losses find themselves drifting toward the sources of the Nile and feed indirectly the GERD.

In the most pessimistic opinions, Egypt could lose 20–23% of its arable lands due to the construction of the GERD. Egypt must therefore embark in all methods to recover water losses by evaporation over the AHDR.

There are also other sources of moisture that come through winds over the north coast, the Delta, and the North Sinai as a result of evaporation of water over the Mediterranean Sea.

9 Recommendations

Various researchers have determined that the Aswan High Dam Reservoir loses between 11 and 16 billion cubic meters of water by evaporation. This large loss justifies the development of the technology of weather modification to avoid sending these losses back to the equator to feed the sources of the Nile including the Great Ethiopian Renaissance Dam.

Weather modification consists of using airplanes and drones to precipitate clouds or the use of dew and fog harvesting technologies to recuperate moisture from the air.

There are two complete different sources of moisture in the air:

- In Lower Egypt, north coast, and North Sinai, mainly from Mediterranean sources, with some from the Nile

– In Upper Egypt and the Nile by evaporation from the Nile

The Egyptian government should collaborate with the World Meteorological Organization to train specialists in weather modifications.

Egyptian scientists and researchers should collaborate with surrounding countries in efforts of weather modification.

Fog and dew harvesting technologies should not be merely copied from other countries.

In the lower layers of the sky, most arid areas of Egypt experience a large inversion of temperature at night due to nocturnal radiation of the ground losing heat to the black sky. This particular phenomenon can encourage the development of special collectors.

Fog and dew harvesting technologies must be capable of resisting the khamsin and strong windstorms.

Old obsolete military airplanes, light airplanes, and airplanes normally used for agricultural aviation should be modified to transport chemicals for two main types of cloud seeding processes:

(a) Glaciogenic seeding – dispersing ice-producing materials in clouds at a temperature below 0°C (probably limited to North Sinai near Mount Sinai or at very high altitude on Red Sea Mountains) or for clouds at very high altitudes
(b) Hygroscopic seeding – dispersing large hygroscopic or salt powders in a cloud, causing particles to grow quickly

Most of the evaporated water over the AHDR climbs to altitudes of 4 km. In high-altitude airplanes, balloons would be needed.

There is a difference between periods of maximum cloud formation over the AHDR and over the north coast. For example, cloud formation is at a maximum on August 2 at Abu Simbel, while cloud formation over the north coast, North Sinai, and the Delta tends to increase in late fall and early winter. Egyptian decision-makers can therefore optimize the use of fleets of aircraft for weather modification.

The technology for manufacture of aircraft dedicated to weather modification is not excessively complex. The Egyptian authorities should adopt national regulations to facilitate the construction of dedicated airplanes through the government-owned aircraft or new private manufacturers.

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Impact of the International Context on the Political and Legal Dimensions of the Aswan High Dam (1952–1960)

Mohamed Salman Tayie

Contents

Abstract The Aswan High Dam (AHD) was the beginning and most strategic base for all developmental projects in Egypt. However, the establishment of the AHD was coupled with highly complex political conditions due to the historical phase Egypt experienced both on the domestic and international levels. At the domestic level, Egypt witnessed a transitional phase in its political history, the transition from monarchy to the republican system in addition to completely ending British colonization. At the international level, this period witnessed the crystallization of the bipolar system and the escalation of the conflict between the super polar powers with the consequent complications in the political and regional interactions, particularly those relating to the AHD.

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It became evident that the international context was the decisive factor in influencing the political and legal dimensions of the AHD since the AHD was politicized as shown in the scientific, political, legal, and economic debates around it, in addition to the political conditionality associated with its financing.

Thus, the study raises the question: What is the impact of the international context (the regional and global levels) on the political and legal dimensions of the High Dam in Aswan?

Keywords Aswan High Dam (AHD), Centurial storage, No harm principle, Political conditionality, Prior notification, Prior notification condition, Tripartite aggression, Water cooperation, World Bank

1 Introduction

> The High Dam is one of the most accurate and dangerous geographical surgeries that man has ever done. It marks a radical change in the natural landscape, a revolution on the Nile as it changed the era of annual storage with that of the centurial storage. This opened up prospects and unparalleled water possibilities as the dam has no match that it rightly marked the golden age in the history of the Egyptian irrigation and agriculture. With the AHD, it became possible to exploit every drop of the Nile water. (Gamal Hamdan [1])

On January 9, 1960, Egypt celebrated the commencement of constructing the Aswan High Dam (AHD) which is considered as the most significant infrastructure project carried out by Egypt throughout its ancient and modern history, the project through which Egypt was able to make a strategic shift in the Egyptians relationship with their immortal Nile.

It is always said that "the Egyptians had changed the geography of the world twice," the first when they dug the Suez Canal and managed to link the old world continents of Asia, Africa, and Europe together while the second when they built the dam and managed to control the hydraulic behavior of the Nile in addition to starting of a new phase of water centurial storage on the Egyptian territory.

As a continuation of previous attempts to control the movement of the Nile, Egypt, under the leadership of Gamal Abdel Nasser, decided to establish a national project that has numerous benefits to the Egyptian State. However, the international context had an impact on this decision as Egypt faced major challenges of which AHD financing was the most important. Another challenge was that the financing was associated with political conditionality that may affect the sovereignty of the Egyptian State. Moreover, some Nile Basin countries, led by Ethiopia, refused this project without legal basis. However, the project had been implemented.

In fact, the AHD was completed on January 15, 1971, at a crucial time that marked a victory for Gamal Abdel Nasser in the battle of constructing the AHD which, in turn, marked a milestone in Egypt's political and economic history.

Since the AHD was the most excellent strategic base for all developmental projects in Egypt, the study raises a question that represents the core of the research problem: What is the effect of the international context (the regional and global) on the political and legal dimensions of the AHD?

The research analyzes this problem during the period 1952–1960 as this was the stage that witnessed the international system's significant impact on the regional and international interactions with the political and legal dimensions related to the AHD.

2 The Colonial Heritage in the Nile Basin

With the Nile Basin countries falling under colonial domination, and more particularly with the British occupation of Egypt, Britain's government recognized the centrality of the Egyptian territory. This centrality was not only due to the significant location securing British transportation to its colonies in India but also to its importance as being a food basket and the economical alternative on which Britain can depend for its growing needs for food. The reason was that Britain wanted to reduce total reliance on the agricultural production in its colonies in India. To achieve this goal, the British government adopted a strategy that primarily aimed at securing the water of the Egyptian territory through holding a number of international treaties and conventions that secure Egypt's share of the Nile water [2].

Consequently, since 1891 until the middle of the last century, eight Agreements concerning the Nile River were signed in the colonial era. These Agreements are [3, 4] as follows: the 1891 protocol between Britain and Italy; the 1902 Convention between Britain and the Ethiopian Empire and between Britain, Italy, and Ethiopia; the 1906 Agreement between Britain and Congo; the 1906 tripartite Agreement between Britain, France, and Italy; the exchanged memorandums between Britain and Italy (1925 Agreement); the 1929 Agreement between Egypt and Great Britain on behalf of Sudan, Kenya, Tanganyika(Tanzania), and Uganda; the 1934 Agreement between Britain (on behalf of Tanganyika – currently Tanzania) and Belgium (on behalf of Rwanda and Burundi); and the exchanged memorandums between Egypt and Britain in the period between January 19, 1949, and January 5, 1953.

After the Nile Basin countries achieved independence, three bilateral conventions were signed between Egypt and some of these countries. These conventions are the convention of full utilization of the Nile water between Egypt and Sudan in 1959, the 1991 Convention between Egypt and Uganda, and the 1993 Convention between Egypt and Ethiopia.

These conventions were characterized by a number of characteristics [5–7]:

1. They are basically bordered Agreements to divide the colonies between the colonial powers. As the Nile River is an international river passing through the territories of these colonies, its managing was considered among the colonial powers through some of the items of those border conventions.
2. Those conventions derive their legitimacy from the basis of "International Succession of Treaties" stipulated in Article (12) of the Vienna Treaty for Conventions 1978.

3. The parties of those conventions were the colonial powers with the absence of any real representation of independent governments representing the Nile Basin countries except the Ethiopian government, which was a party in a number of conventions especially the 1902 Convention, as Ethiopia was not the subject of colonialism except for a short term.
4. Those conventions guaranteed preserving Egypt's share of the water, while preventing any project that would affect this quota either through controlling the river or through the establishment of dams or water barriers on its course or even on the lakes that are its source.

3 The Politico-Historical Context for the Construction of the AHD

Although the Nile is the lifeline for the Egyptians, the backbone which the Egyptian State depended on throughout its history, it was a source of threat whether on the local level or on the external level, regional and international. On the local level, the Nile flood and its drying up had a great effect on Egyptian life with its political, economic, and social components [8]. On the regional and international level, the political turmoil and instability imposed itself on the political environment of the Nile Basin and the hydrological regime. Hence, the Nile Basin became a center for political conflicts between a number of different regional and international powers. It is notable that the political conflict over the Nile has started since the 1950s of the twentieth century and particularly with the construction of the AHD [9].

The AHD was constructed amid a critical and challenging historical period both on the internal and external levels. On the level of the Egyptian domestic politics, the beginning of the 1950s, mainly July 23, 1952, witnessed the Free Officers Revolution which had a high impact on the current Egyptian State. This revolution marked the turning point that contributed to the declaration of the end of the British protection of Egypt entirely and the transition from monarchy to a republican presidential system. This period also witnessed Gamal Abdel Nasser's adoption of agrarian reform policies. To implement those policies, it was required to provide the necessary water. This period also witnessed "Abdel Nasser's" desire to adopt a project that would mobilize the masses around it. This was represented in the AHD project which did not only represent a dam that would be replaced with the project of Aswan Reservoir but, rather, represent a national dream, a political project that gathers different categories and forces of the people around it, and contribute to the increase of political loyalty to the government while promoting the political legitimacy of the political system itself. On the international level, the 1950s of the last century witnessed the beginning of the cold war and polarization between the Western camp led by the United States and the Eastern camp led by the Soviet Union [10].

The announcement and implementation of this project hence witnessed several stages as follows:

3.1 Planning Stage

3.1.1 The Idea of Establishing the AHD

As a result of the inability of the annual storage method – which means water storage in times of the flood peak and using it in water shortage months – to provide Egypt's water needs and overcome the problem of the volatility of the annual revenue of the Nile, and in the light of the considerable increase of water needs for the Egyptian development purposes, constant storage or the so-called centurial storage began to be considered.

An extensive controversy then began in Egypt on the most appropriate projects for the centurial storage for the Nile water. Among the most critical ideas proposed for the centurial storage were the equatorial lakes and the Ethiopian ones specifically lakes "Victoria," "Kyoga," and "Albert" in the plateau of the equatorial lakes in addition to Lake "Tana" in the Ethiopian plateau. Those ideas were raised in the 1920s when the British Expertise House "Rupert Murdoch Macdonald" proposed an integrated project for centurial storage to the Ministry of Public Works and Water Resources engineers. The project included the construction of arches (bridges) at "Nagaa Hammadi," and they were set up in 1930. The project also included setting up a dam at "Sennar" for Sudan in 1925 and also setting up a dam at "Jabal Al-Awliya" in 1937 to store water for Egypt. However, the project proposed by the British Expertise House included other projects which were not implemented. Among these projects were setting up a dam at Lake "Albert" in Uganda and setting up another one at Lake "Tana" in Ethiopia [11].

These projects faced strong objections, but Egypt's increasing water needs and thus its need to start the centurial storage projects prompted the Egyptian government to form a committee of senior irrigation personnel in the Ministry of Egyptian Public Works and Water Resources to study the proposed projects for the centurial storage. The committee submitted to the Council of Ministers a program containing a number of projects, and the Council of Ministers approved the program in December 1949. These projects could save about 13.2 billion cubic meters at Aswan after subtracting losses by evaporation. The initial estimation of the costs of the proposed projects was approximately 122 million Egyptian pounds.

The Egyptian Ministry of Public Works actually started to implement one of these projects in agreement with Uganda in the "Owen Falls" at the northern exit of Lake "Victoria" toward Lake "Kyoga" to generate electricity for Uganda and to store water in Lake Victoria for Egypt. The dam was then established and began to generate electricity for Uganda, but storing water for Egypt in the lake did not start. The reason was that it required the approval of Kenya and Tanzania while considering the necessary compensation to be paid by Egypt because of the high level of the lake [12].

3.1.2 The Aswan High Dam: A Stroke of Genius

While the Egyptian Ministry of Public Works was preparing for the centurial storage project mentioned in advance, a businessman in the field of agriculture named "Adrian Daninos," an Egyptian of Greek origin, was wandering in the area of the Nuba to do some work. Through his impressions of the river and the geological nature of the region, he had a genius idea, which is the establishment of a large dam in the narrow region south of Aswan. This dam was planned to be of a high altitude to allow for Egypt the idea of centurial storage. It was also meant to guard Egypt against the dangers of high floods, to secure storing huge amounts of water annually to be used in the years of the Nile low revenues. Moreover, it was also planned for the dam to generate a massive electric power through draining water from behind the dam to the Nile in front of it. However, Daninos' genius idea was not based on any hydraulic or topographic study, and thus it did not receive due care from the Egyptian government.

In 1952, with the revolution of 23 July, the Egyptian government began to study the projects proposed for the continuous or centurial storage of the Nile water. For many reasons, this government found that the idea of a High Dam in Egypt is the best option for Egypt. The reasons that led the government to give priority to the idea of establishing a High Dam rather than the idea of the centurial storage in the lakes were based on the fact that the project of the High Dam lies in the Egyptian territory and thus Egypt is ensured that neither Britain nor any other country would dominate that project. Moreover, the expected revenue from storage in the lakes is limited compared to the expected revenues from the construction of the High Dam. Therefore, it would be more beneficial for Egypt to reserve flood waters by means of a High Dam in Aswan instead of constructing a number of projects on the tropical lakes and the Ethiopian Lake Tana. Also, the establishment of the High Dam also included the generation of substantial electric power, which the Egyptian government considered necessary to serve Egypt's industrialization and comprehensive development projects.

On October 8, 1952, while the revolution was still at its peak, a decision was issued by the Revolutionary Command Council to start studying the project of the AHD [13].

3.1.3 Scientific Debate on the High Dam in Aswan

A number of engineers and hydrologists discussed at the New Delhi Conference of Large Tanks in 1951 the idea of establishing a High Dam on the Nile to store large amounts of flood water, taking into account the siltation. Their discussion concluded that such a project could be implemented [14].

A large number of engineers of government agencies in Egypt began extensive researches in the proposed dam area south of Aswan in addition to the area that would form the reservoir that would be located in front of the dam and which extends up to Wadi Halfa in Sudan. Egyptian experience contributed to this study with a team that carried out many technical types of research for the project and made use of the Egyptian Air Force to create aerial photographs. The government also made use of a technical mission from the German company "Hochtief" – which was associated with another company, Dortmund – to study the possibility of constructing the dam and determining the appropriate place for its establishment. In turn, the German company submitted a preliminary technical report in March 1953 [15, 16].

In 1954, a committee of experts specialized in the design and implementation of dams was invited to study all aspects of the AHD project. A meeting was held on November 15, 1954, to come up with a final and decisive judgment in relation to any major or subsidiary issue. This enlarged meeting included a number of Egyptian experts in addition to the world's greatest experts in establishing dams [17, 18].

The most prominent international experts who attended that meeting were:

1. Carl Trzacki from Winchester, Massachusetts, was a well-known expert in dam design, and he also gained considerable fame for his invention of the modern foundations of soil science and foundation engineering.
2. A. S. Steele is also an American from Piedmont, California, and was a vice president and chief engineer of the Pacific Gas and Electric Company in San Francisco, California.
3. Lorenz Straub, an American from Minneapolis, Minnesota, was head of the Civil Engineering Department and director of the Hydroponics Laboratory at Saint Anthony Falls at the University of Minnesota.
4. André Quinn was a French expert of international renown because of the mastermind overseeing the design and construction of more than 50 dams of large dams.
5. Max Proussi, a German from the city of Aisen, had previously designed many reservoirs to provide water in the Ruhr area of Germany and supervised the installation of reservoirs.
6. A. Iche is the director of the French company Soletanche. He was very experienced in the modern methods of injecting the foundations of the dams, including the dams established on the sand deposits.

The experts' committee decided to choose the location of the 6.5 km south of Aswan as the most suitable site for the construction of the body of the dam. The committee also confirmed the technical competence of the AHD project [19, 20].

The International Bank for Reconstruction and Development (IBRD) also issued in February 1955 a report on the AHD project on which the third item states:

> The AHD project is technically sound as its capacity ensures the utilization of the largest amount of the Nile water. Moreover, it is not inconsistent with the so-called centurial storage projects but is complementary to them since the continuous storage in the tropical lakes helps mitigate the intensity of wet and dry sessions. At the same time, the AHD will store flood water annually to mitigate the annual short-term fluctuations in the river revenues. Hence, this project could be more successful than other proposed storage projects that fail to meet the irrigation needs contrary to the AHD project [21].

3.1.4 The Economic Debate: The Battle of the Dam Financing and the Political Conditionality of the World Bank

The various local and international bodies that participated in the debate about the economic costs, expected economic returns, and economic feasibility of the AHD had agreed on the tremendous economic feasibility of establishing such a project.

Three months after taking his power, Gamal Abdel Nasser announced the AHD project and hence dating what is known as “the AHD era.” With this announcement, the Nasserite regime began to seek mass mobilization to strengthen its political legitimacy. Much in the same way, “Abdel Nasser” started to seek the support of one of the major countries so that its research and engineering institutions may contribute to the planning for the AHD. The road was paved for the Egyptian government, especially after the German government announced that it would pay the Jews compensations for the damages caused by the Holocaust, and in order for Germany not to lose Arabs in international forums, it announced that it would finance planning for the construction of the AHD. This was done in November 1952 by the German companies “Hochtief” and the “Dortmund” Union. The two companies completed their design in 1954, and it was accepted and approved by the Egyptian Ministry of Public Works. However, this design was rejected by the International Bank for Reconstruction and Development (IBRD) considering it to be nonconforming [22].

Despite the overwhelming popularity of the AHD project, yet this was not enough to finance its construction. It was estimated that the cost of constructing the dam and its hydropower station would be about LE 210 million and would be up to 400 million Egyptian pounds if the rest of the project costs of irrigation, drainage, reclamation, housing, facilities, and roads was added. In addition to these costs, there was the interest and compensation for lands that would be flooded in Egypt and Sudan. These enormous costs were difficult for Egypt to bear alone. This prompted the Egyptian government to seek external sources to contribute to the financing of the AHD project, in particular, the financing of the import of equipment and machinery for its implementation.

In the beginning, Egypt headed to the Western countries and the World Bank to finance the construction of the dam, and then in 1955, a British construction company began to adopt plans for the High Dam project after the German project was rejected by the World Bank. With this step, Egypt hoped that it would achieve the support of the World Bank. However, this was not achieved.

In spite of the World Bank’s assessment of the safety of the dam project on the economic level, yet it began to call into question Egypt’s ability to secure the free currency necessary to finance the construction of the project. The World Bank pointed out that Egypt’s need for foreign currency for the completion of the AHD project amounted to about 400 million dollars, whereas Egypt’s economic ability to borrow does not exceed 100 million dollars. This amount was what the World Bank had shown its willingness to lend to Egypt, noting that the governments of the

United States and Britain were willing to participate in the project and that their contribution would be presented to Egypt in the form of grants. The World Bank's skepticism about Egypt's ability to raise funding for the AHD project was a kind of pressure on Egypt to push it toward the United States and Britain, which both had a desire to impose their political and economic conditions on Egypt either directly or through the conditions put forward by the Bank on Egypt to participate in financing the construction of the dam [23].

However, another issue was debated between Egypt, the World Bank, and other international players. The issue was the subjection of the AHD implementation contracts to competition between international companies in accordance with the Bank's policy regarding the projects which it has a share in their financing.

The Egyptian side tried to show some flexibility by suggesting adding an American company to the German group "Hochtief" to be more representative, or, more accurately, so that the United States would have a company among those that would implement the project in the hope that the United States would reduce its covert and overt resistance to the project.

The World Bank, for its part, showed some flexibility when it proposed that the first phase of the dam construction would be appointed to Consortium "Hochtief," while the second phase would be based on competition. However, the United States rejected this and insisted that it would not participate in financing the project unless the first and second stages of the dam were contracted on the basis of competition between the international companies wishing to participate in its construction. In turn, this forced the World Bank to retract its flexible stance in favor of the American uncompromising position [24].

The certification of "Eugene Black," the President of the Bank – in the program for recording the oral history in 1969 – was a recognition of the strangeness of the American-British demand, where he said:

> I went to Cairo in February 1956 to obtain Egypt's approval of the terms of financing the AHD. The most important of these commitments was that Egypt would not hold any other foreign loans throughout the project implementation period. This condition was unprecedented in all of the World Bank contracts. However, I found that The US government insisted on this condition [25, 26].

The World Bank's director "Eugene Black" was shocked when he felt he had played the role of a doll in the hands of "Dulles," the US Secretary of State, and Mr. Eden, the British Foreign Secretary. Thus, he said:

> Dulles has no control over the Egyptian economy ... This is the World Bank's task, and the Bank had assigned us to answer two specific questions: Is the project possible? and Does the Egyptian economy bear the burden of repaying the loans? Indeed, the Bank affirmed the two questions. But, Dulles justified the American stance telling Eugene Black that "the Congress did not approve enough foreign aid to supply Tito in Yugoslavia and Nasser in Egypt ... and that he – Dulles – would prefer to provide aid to Tito, who is far from the communist bloc than Nasser [27].

By the end of 1955, the Israeli forces launched an unexpected attack on the Egyptian forces positioned in Gaza, which prompted Nasser – by means of the Czechoslovakian mediation – to depend on the Soviet Union to obtain weapons and military equipment. The Soviet Union also expressed its desire to adopt planning funding for the project and its establishment, which made "John Foster Dulles," the US Secretary of State, and his British counterpart, "Eden," to feel at risk.

Consequently, the World Bank, the United States, and the United Kingdom announced their combined funding of 270 million US dollars. But this sum did not meet the Egyptian expectations as the total cost of the project was about 1.5 billion US dollars, which was equal to 500 million LE. However, the Egyptian government considered it as a step in the right direction and agreed on the finance. Nasser also agreed to the US conditions late in July 1956, including the condition that determined Egypt's external debt and restricted its freedom to hold other loans during the implementation of the AHD [28].

Nasser's position was farsighted because he wanted to invalidate the last pretext for the Americans and the World Bank to renounce financing the AHD. However, the United States refused to finance the project, and the US Secretary of State declared this rejection to the Egyptian ambassador in the United States on July 19, 1956, saying:

> The United States had changed its view on the issue of the AHD and that it now apologizes for any negotiations on financing the project. Among the reasons for this was that one of the poorest countries cannot afford the costs of one of the largest projects and that the Nile is not a sole Egyptian property, as there are others on the river whose views are different from the Egyptian. To be declared, this decision was taken after consultations between the President and Congress.

On July 20, 1956, the US State Department issued a press statement confirming this rejection declaring it to the whole world. This statement declared [29]:

> The United States is convinced that the Egyptian government is not able to provide the local currency necessary for financing the dam because the implementation of this giant project will impose austerity on the Egyptian people for 12–15 years. A condition that the Egyptian people cannot afford. Moreover, the American government does not want to bear such responsibility.

In response to this American refusal to participate in the financing of the AHD, the Egyptian response was not delayed. The late Egyptian leader Gamal Abdel Nasser delivered his historic speech on July 26, 1956, discussing the whole issue of the AHD and its financing. He said:

> The High Dam project was presented to us in 1952, we studied it and found that it was sound and that it would end ten years later. We faced the funding obstacle. We contacted the World Bank and asked them to contribute to financing the project. But, they said there were obstacles; the English and the Israelites, so when you end your disagreements with them we can finance the project ... They also said: you do not have a parliamentary system to hold a referendum on the project and we understand from this that we would not get help from the Bank . . . So we decided to rely on ourselves and on industrial companies . . . The World Bank said it was willing to lend us 200 million dollars over 5 years, during which we would spend 300 million dollars ... The World Bank confirmed that the loan depends on specific conditions which are: to assure the Bank that the foreign exchange that Egypt would receive from the American and English grants would not be not interrupted, and that the bank should agree with the Egyptian government on controlling the public expenditure of the State. The Egyptian government should also not bear

> any external debt, and that no payment agreements should be signed until after reaching an agreement with the World Bank and prior to agreeing on any project.
>
> The bank requested that the project's management be subject to agreement with it. We spoke with representatives of America and told them that in a period of 5 years 370 million dollars would be spent on the dam, of which Egypt would pay 300 million and you pay 70.We also told them that the project would cost about 1 billion dollars ... How can I implement the conditions dictated by the Bank?
>
> During such time, the Russian ambassador came and said that Russia was ready to participate in the financing of the AHD. That was after December 1955. I told him: we were having talks with the World Bank . . . Thus the discussion of the details was put off. The Americans knew that there was a Russian offer. Hence, the World Bank director sent a letter asking for his invitation to come to Egypt. The Bank director then arrived and started negotiations in February 1956. When I met him, I said to him: "Frankly, we have a problem with the terms of the loans and interest because we have been victimized by the occupation because of the loans. We would not accept any harm to our sovereignty.
>
> It was supposed that we should start the project in June 1956. So, I informed the Bank director that we would not start the project unless a deal was achieved with the Bank. The Bank director said that we should settle the problem of water with Sudan and then the Bank would sign the agreement with us [30].

In his speech, Nasser discussed the US withdrawal of its proposal and its attempts to provoke Ethiopia, Uganda, and Sudan against the project. He also discussed its attempt to question the ability of the Egyptian people and economy to bear the costs of the project. Then the president put forward the alternative solution of financing the AHD, saying:

> The Suez Canal income in 1955 amounted to 35 million LE which equals hundred million dollars. Then, the solution is to get money from the Canal.

It was evident from Nasser's speech that he started by choosing the West, headed by the United States, as an external party that could contribute to the financing of the AHD. Nasser tried hard to make this funding part of a productive cooperative relationship with the West provided it did not affect Egypt's independence. But the Western countries did not accept the idea of contributing to the AHD project [31].

3.2 Struggle Stage for the Implementation Reaching the Tripartite Aggression

This phase was characterized by putting pressure on Egypt through the water issue by creating a heated political debate about the AHD project. Then, the situation developed after the tripartite aggression against Egypt based on the Suez Canal and the High Dam crisis.

3.2.1 Political Controversy Over the AHD

Among the political controversies over the AHD, which were raised even before its implementation, was the issue raised by the World Bank about the constitutionality of the Egyptian government and its ability to agree on external commitments. The Egyptian government's position on this issue was decisive as it did not accept any question about its constitutional legitimacy. The Egyptian government also announced that it had already signed with Britain the agreement on the evacuation of the Suez Canal area in July 1954, which included the financial and political obligations on the side of Egypt. So the World Bank's question of the constitutionality of the Egyptian government was merely to put pressure on the Egyptian government's position, which made the Bank appeared more uncompromising than Britain. However, this issue was resolved by the World Bank's acknowledgment that the government of the revolution is the actual government of Egypt and which was recognized by all the member States of the World Bank. Consequently, it became possible for this government to receive loans from the World Bank [32].

3.2.2 Tripartite Aggression on Egypt

Following the Egyptian government's approval of the World Bank's offer, the World Bank announced that it would open tender for the construction of the dam to all companies. However, the Egyptian government did not favor this option as it desired to give the implantation to the two German companies which developed the initial design of the dam. This coincided with internal American pressure, especially from the Jewish lobby, to influence the decision-maker to stop this funding. Consequently, the British and American governments announced their withdrawal of the funding of the AHD, a decision which "Gamal Abdel Nasser" considered a hostile stance against Egypt.

Nasser found himself facing one of two options: either to surrender to the will of the United States and Britain or to seek self-reliance in funding the AHD. In response, Nasser announced the closure and nationalization of the Suez Canal. The nationalization of the canal aroused the anger of both France and Britain which declared a military campaign against Egypt. In the meantime, Israel exploited this situation to intervene in the Suez Canal. Moreover, the history of the tripartite aggression against Egypt coincided with the declaration of Ethiopia's right to freely utilize its waters in the Blue Nile to establish a number of projects that may contribute to the Ethiopian domestic development. On the other hand, skirmishes between the Sudanese government, hostile to the Egyptian ruler, and the Egyptian government increased as a result of the AHD project.

However, the issue ended with the withdrawal of the tripartite troops, and Egypt regained its sovereignty and ownership of the Suez Canal. This provided Egypt with additional economic capacity that helped meet the costs of constructing the AHD [33].

3.3 The Breakthrough Phase and Construction Commencement of the AHD

The situation continued as it was until 1958, where the unity between Egypt and Syria contributed in supporting the Egyptian position. Egypt then began to take serious steps to study the Soviet offer of participating in the financing of the AHD construction. After a short negotiation, on December 27, 1958, Egypt signed the Soviet Loan Agreement to finance the first phase of the AHD construction. This included the construction of the AHD to the extent that would make it possible to direct its water into a new course while increasing the available annual storage.

The agreement stipulated that the Soviet Union would provide Egypt with a loan of 400 million rubles, or about 34.8 million Egyptian pounds, which would be used to import machinery and equipment not available in Egypt in addition to covering the expenses of the Soviet specialists and technicians who were employed in the implementation of this phase of the AHD as agreed by the two parties. The loan was to be repaid in 12 installments per annum starting in 1964 at a rate of 2.5% per annum.

Despite the tensions between Egypt and the former Soviet Union in 1959 due to the police attack on Egyptian communists, yet this did not affect the course of the agreement concerning the Soviet participation in the financing, design, and implementation of the AHD [34].

In this context, the Egyptian government supported those who support the Egyptian side in Sudan who came to power in 1959. Consequently, this contributed to holding the 1959 Agreement to utilize the Nile water between Egypt and Sudan. This Agreement then served as the legal framework on which the Egyptian side relied to complete the legal construction of the AHD. This does not preclude the fact that this Agreement had been accompanied by extensive controversy, because of the opposition of a number of international parties, especially the Ethiopian side [35, 36].

On August 27, 1960, an Agreement was signed announcing the Soviet Union participation in financing the completion of the AHD project. Under this Agreement, the Soviet Union government provided Egypt with 900 million rubles (78 million Egyptian pounds) to cover the costs of the project design, research and studies, supply and installation of gates and hydroelectric units, and equipment for irrigation projects [37].

4 The Legal Dimensions of the AHD

The construction of water dams on international rivers requires discussing the legal dimensions of these dams and how they affect other countries bordering the international river.

The Nile River derives its particularity as the most extensive river among its counterparts around the world, and the current data indicate that it will also be the river that will spearhead international conflicts over water. Given the legal dimensions of the High Dam, the dam raises the issue of international legal principles relating to international rivers, as well as to water projects on the international river. Among the most important principles are [38] as follows: "the no-harm rule, protection of the acquired historical rights, prior notification, international cooperation, equitable and reasonable utilization, peaceful settlement of disputes, non-abuse of the use of the rights, and good-neighborliness."

In the Egyptian case at the time of establishing the AHD, the Egyptian decision-maker had to take into account the legal dimensions of the construction of the dam.

One of the most important political and legal issues about the AHD project raised by the World Bank and Britain was that the Nile River is an international river; therefore, the river basin countries must approve it before proceeding with its implementation. In the 1955 World Bank report on the AHD, it said:

> Abyssinia (Ethiopia) and Uganda had expressed concerns about the implementation of the AHD project, but the data available to the Bank in this regard indicated that these two countries would not be harmed as a result of that project... And that an international agreement between Egypt and Sudan should be signed to approve the AHD project as the project's reservoir would flood some of the Sudanese lands for which the Egyptian government should pay due to compensations. The Egyptian and the Sudanese governments took positive steps to agree on the distribution of the additional water gained by the project between the two countries which was estimated at 18.7 billion cubic meters. However, negotiations between Egypt and Sudan had begun in late 1954, and many opinions and suggestions were exchanged, but the two governments did not agree on this matter [39].

In an unstable political climate, it was difficult to reach political solutions that may serve the legal side, although the effects of the AHD were exclusively limited to the Egyptian and the Sudanese sides [40, 41].

The legal dimensions of the AHD can be discussed through three legal principles: the AHD and the "Prior Notification Condition," the AHD and the principle of "no harm," and the AHD and the principle of "Water Cooperation":

4.1 The AHD and the "Prior Notification Condition"

Prior to the construction of the AHD, Egypt had to reach an agreement with the Nile Basin countries about its construction. The Egyptian government had to reach such an agreement as this project only affects Sudan because the reservoir of the dam water would extend in the Nuba area in northern Sudan, in addition to its extension in the Nuba area of Egypt. However, there were some obstacles in the face of this agreement, which were then settled on November 8, 1959, with the ratification of the two presidents Gamal Abdel Nasser and Ibrahim Abboud of what was called the "Nile Water Agreement."

Under the 1959 Agreement, Sudan agreed on Egypt's constructing of the AHD on condition that Egypt would pay 15 million Egyptian pounds as compensation for Sudan for the flooding of the ancient city of Wadi Halfa and the 150 km southward the region that later became part of Lake Nasser. At the same time, Egypt agreed on Sudan's construction of "Roseries" reservoir on the Blue Nile and "Khashm El-Girba" tank on the "Atbara" river to accommodate the displaced residents of the Sudanese Nuba there. The Agreement also resulted in the distribution of the water to be provided by the High Dam, which amounts to 22 billion cubic meters, between Egypt and Sudan instead of going to the Mediterranean. With this Agreement, Sudan would have 14.5 billion cubic meters, while Egypt would have only 7.5 billion, which meant that Egypt's annual total share of this water is to be about 55.5 billion cubic meters on average [42, 43].

What is mentioned above proves Egypt's commitment to the condition of "prior notification" before the construction of the AHD. This is evident since it notified Sudan of that project and discussed different water, environmental, engineering, and financial issues related to the AHD and its potential impacts.

4.2 *The AHD and the "No Harm" Principle*

The "no harm" principle is one of the most critical customary rules of international law, which in turn has become a binding legal basis after being adopted and emphasized in Article VII in the UN Convention on the Law of the Non-Navigational Uses of International Watercourse in May 1997.

It thus became an international legal norm for all States, whether or not they were signatories to this Agreement. The text of the article was as follows:

> Watercourse States shall, in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States.

The drafting of this Agreement came after a long argument raised by a number of the upstream countries, headed by Ethiopia, where there was an objection to include such a text. The upstream countries considered that this text would be incompatible with the realization of States' sovereignty and independence while making decisions on internal projects on the international riverbed. The wording was put in this way to satisfy all parties since the requirement of no harm was no longer absolute as a condition was included that the harm would not be a significant one [44].

The principle of "no harm" can be discussed through reviewing the benefits of the AHD for both Egypt and Sudan while comparing these benefits with the damage caused by its establishment. It is notable that all the negative effects resulting from the establishment of the AHD were limited to the downstream countries, Egypt and Sudan, and that none of the upstream countries were negatively affected. This proves clearly the presence of the "no harm" principle in the case of the AHD construction.

4.2.1 Advantages of the AHD for Egypt and Sudan

The World Bank February 1955 report confirmed that although the cost of constructing the dam was high, yet it was reasonable given the many economic and financial advantages that the project would provide. The report identified the positive results expected from the project in 1955 with the following [45, 46]:

1. *Increasing water revenues:* thus saving about 19 billion cubic meters of water in Aswan. In consequence, this would increase Egypt's ability to meet the development requirements in agriculture, industry, tourism, and construction.
2. *Transforming periodical irrigation areas into permanent irrigation*: this land amounted to 670 thousand acres, according to the World Bank report in 1955, while some studies estimated its capacity of about 973 thousand acres. This resulted in an increase in the crop area in Egypt by about 6% [47]. In turn, this resulted in an increase of about LE 100 million pounds per year GDP, equivalent to about 255 million dollars annually according to estimates of that time [48].
3. *Increasing the agricultural area*: the total reclaimed land amounted to about 1.789 million acres from 1968/1969 to 1996/1997. The expansion of agricultural land has increased the capacity of the agricultural sector to absorb labor [49].
4. *Increasing agricultural production and improving the productivity of the agricultural land*: enabling farmers in Egypt to grow some crops such as corn, cotton, and other crops in the most appropriate climatic conditions.
5. *Increasing agricultural income* by 45% as a result of the abovementioned [50, 51].
6. *Increasing the State budget* by about 300 million pounds from selling the lands that would be reclaimed and cultivated with water, which would be provided by the AHD. This meant that the AHD would provide Egypt with income more than the total cost in just 2 years [52].
7. *Generating electricity from the hydroelectric dam station*: the contribution of the AHD in electricity generation in Egypt, compared to the total consumption of electricity, increased from 2% (71 million kilowatt hours) in 1967 to 52% (1,438–6,058 million kWh) between 1968 and 1976, then 54% (8,152 million kWh) in 1978, and 37% (8,632 million kWh) in 1982. On his part, the former Egyptian Minister of Electricity, Engineer Maher Abaza, declared that:

   > The High Dam saved Egypt about 4 billion dollars annually which would have been spent on the construction, operation, and maintenance of thermal plants to generate electricity [53].

   This saving of electricity by the AHD accelerated the electrification of rural Egypt. This has contributed to an increase in education and small- and medium-sized enterprises, in particular poultry farms, small textile factories, dairy factories, and other industries and workshops, thereby increasing productivity.
8. *Protecting Egypt from the dangers of floods*: Before the construction, the AHD high floods caused heavy losses and the dumping of some land, villages, and animals and hence the spread of diseases and epidemics. Egypt borne a lot of costs to cope with these floods, thus exacerbating the problem of drainage and reducing production. The Egyptian authorities estimated the annual loss of national income as a result of these two factors as about 10 million Egyptian pounds [54].

   If it had not been for storing the water in front of the High Dam, the costs of resisting that flood would have been worth more than 100,000 feddans whose losses were estimated at more than 10 million pounds in the 1960s [55].

9. *The AHD saved Egypt from drought risks*: The High Dam did not only protect Egypt from the high floods in 1964, 1967, 1975, 1988, 1996, and 1998 but stored the water of these floods as a vital balance of water for use in the years of low revenue as well.
   Egypt had with dawn from the reservoir of Lake Nasser about 4 billion cubic meters of water between 1976 and 1980 and then withdrew about 88 billion cubic meters of the lake reserves between 1981 and 1988.The volume of losses the AHD saved Egypt from in the year 72/1973 was estimated by about 250 million pounds [56].
10. *The AHD and navigation improvement in the Nile*: the increase in the Egyptian national income as a result of improved navigation and river transport in the Nile, after the construction of the AHD, amounted to between 2 and 5 million pounds annually at that time [57].

4.2.2 Damages of the AHD on Egypt and Sudan

Despite the high positive aspects of the AHD, yet its establishment had a number of negative aspects that affected only and exclusively Egypt and Sudan. These negative aspects are represented in [58, 59]:

(a) The flooding of the Nuba and the displacement of its population in both Egypt and Sudan for the establishment of AHD and Lake Nasser, which was formed as a result of the water collected in front of the AHD.
(b) Increasing the salinity and desertification of the agricultural soil as a result of the lack the Nile silt in the Delta compared to what was used to be before. Hence, much talk is raised about the erosion of the Nile Delta shores in the Mediterranean Sea.
(c) Risks related to any crack in the structure of the dam.
(d) Evaporation and leakage from Lake Nasser [60].

Through the previous presentation of the advantages and disadvantages of the AHD and applying cost-benefit analysis to it as an economic and developmental project, and by analyzing the advantages and benefits of it – comparing them with the disadvantages and negatives resulting from it – it is evident that the positive effects outweigh the negative ones. Moreover, the AHD adverse effects have been limited only to the downstream countries (Egypt and Sudan). This refers to the fact that the upstream countries have never been affected by its construction.

In other words, the establishment of the AHD did not affect the amount or quality of water flowing into the Nile River nor did it pollute the river. The AHD construction did not also cause any change in the Nile River ecosystems throughout its course. The most crucial issue in this regard is that the construction of the AHD at this site between the two downstream countries has not affected the current and future water uses of the upstream countries. The dam does not constitute an impediment to any of the Nile countries to have an equitable and fair use of the waters and resources of the Nile River. This, once more, confirms the consistency of the AHD and the principle of "no harm" [61].

4.3 The AHD and the Principle of "Water Cooperation"

The accurate and appropriate implementation of the "fair use" principle necessitates that all the onshore States become obliged to cooperate with one another to achieve the utmost of the river interests and advantages instead of conflicting to chase narrow national interests as the nature of the river is – in itself – a mutual resource for those states. In addition, this cooperation meets the core of the principles of good neighboring and goodwill which are supposed to govern the relations among those States.

In the case of the AHD, an understanding was reached between Egypt and Sudan on the issues related to the dam in the wake of the military coup in Sudan, which was led by the Lieutenant-General Ibrahim Abboud in November 1958. Then 1959 came to chronicle a breakthrough in the Egyptian-Sudanese relations embodied in the Agreement on full utilization of the waters of the Nile between Egypt and Sudan in 1959 to reach an agreement on the establishment of the AHD and distributing the resulting benefits between Egypt and Sudan.

It is the first agreement between two independent States located in the Nile Basin regarding the establishment of the High Dam and the distribution of the resulting benefits between Egypt and Sudan. The Agreement is an example of cooperation among the onshore States for the purpose of using the waters of the international river. It aims at achieving common interests for both States without harming the historical rights of the signatory parties or other States located on the Basin [62]. The Agreement was signed in Cairo on November 8, 1959, and was implemented starting on November 12, 1959. It asserted the obligation to respect the "acquired rights" of each party and identified those rights precisely to avoid any dispute. In its first Article, it recognized the acquired rights of Egypt which equal 48 billion cubic meters per year and 4 billion for Sudan. In the domain of the river regulation and the distribution of the interests of those projects, both parties agreed – in the second Article – to build the High Dam and share its interests; they also agreed that Egypt will financially compensate the Sudanese citizens who were harmed by this establishment with 15 million Egyptian pounds [63]. In fact, the Agreement also adopted the principle of "not to harm other States" while conducting the ordinary relations with others regarding the river. In addition, it adopted the principle of cooperation among the onshore states and considered the regulation of compensation procedures when a State is harmed as a result of the establishment of the High Dam. The Agreement respected the rights of the others in the waters of the river and adopted the principle of prior notification in regard to any private project.

Those principles are considered as the milestone of the current international rivers law [64].

The Agreement of 1959 recognized the rights of the other States in the Basin and dealt with the methods necessary to handle them. The second item of the fifth Article of the Agreement reads: "in case a State located on the Nile is demanding a quota of its water, Egypt and Sudan shall agree to study the demands of such State together and agree on a unified opinion about them, if there was a possibility to accept the assignment of any amount of water for a State, this amount -calculated at Aswan-will be deducted equality from the shares of both States" [65].

5 Regional and International Stance Toward the AHD

Since Egypt's announcement of its intention to establish a huge water project on the waters of the Nile in Aswan, several international and regional reactions were raised. These reactions were mostly opposed to the construction of the dam to the extent that the conflict intensified, especially with the existence of a political environment to stimulate the escalation of the situation against Egypt. Hence, the importance of examining the regional and international reactions toward the dam will be analyzed as follows.

5.1 Regional Stances

5.1.1 The Sudanese Stance

With the arrival of "Abdel Nasser" to power in Egypt and the Sudanese decision to obtain autonomy and independence from Egypt and Sudan, in addition to "Abboud's" taking over of the government, Sudan began to declare its rejection of the establishment of the AHDas, and it was incompatible with the project of the "Roseries" dam on the Blue Nile. This led to the escalation of Egyptian-Sudanese tensions to the extent that led Sudan to declare its noncompliance with the 1929 Agreement to share water with Egypt.

However, there had been many contacts between Egypt and Sudan, but they failed due to the British attempts to create an atmosphere of discord between Egypt and Sudan. Then, the tension escalated with a nonexistent dispute on the Egyptian-Sudanese border raised by the government of Sudan in February 1958 when it included parts of the Egyptian territory in its division of the Sudanese constituencies, although the official maps issued by the government of Sudan itself supported the subordination of these areas to Egypt. The Sudanese government also transgressed the borders set by the Nile Water Agreement for storage in the "Sennar" reservoir in a way that would harm Egyptian agricultural interests. However, the Egyptian government dealt patiently and flexible with the excesses of the Sudanese government [66].

Interestingly, the British Foreign Office offered to mediate between Egypt and Sudan, but Abdel Nasser refused this mediation considering Britain as not neutral to be trusted. This was mentioned by Abdel Nasser in his speech on July 26, 1956.

But with the coup against the rule of the Lieutenant-General "Abboud" and the arrival of a government loyal to the Egyptian side, the dispute was resolved between the two sides, and the 1959 Agreement was concluded to strengthen joint cooperation in aspects related to the Nile water [67].

The government of Sudan demanded that Egypt should pay 15 million Egyptian pounds for the damages to the Sudanese properties resulting from the storage at Lake Nasser in front of the AHD. In addition, Egypt should also give compensations for the deportation of the inhabitants of Halfa and other the Sudanese residents whose lands would be flooded with water so that they would be deported entirely before July 1963.Moreover, Sudan declared that it would not participate in any financial burdens of the costs of constructing the AHD [68]. Sudan government also called for a particular share of the water to be provided by the AHD and which was lost in the Mediterranean Sea and was estimated about 22 billion cubic meters annually. Sudan demanded that the new quota be divided by (2:1) whereby Sudan would receive an additional 14.5 billion cubic meters while Egypt would receive 7.5 billion cubic meters. Indeed, Sudan had what it wanted as Egypt agreed to all of the Sudanese demands [64].

5.1.2 The Ethiopian Stance

The apparent disagreement between Egypt and Ethiopia began after the revolution of July 1952 in Egypt when Egypt decided to build the AHD without consulting the upstream countries. But Ethiopia strongly opposed this and affirmed its right as an upstream country to be consulted in the establishment of the AHD under the pretext that this was one of its rights in the Nile water [69].

The problem was escalated when Ethiopia declared in the "Ethiopian Herald" in February 1956: "Ethiopia is no longer obliged by the Agreements and protocols signed during Minilik II era and that it has the right to exploit the waters of the Nile that runs within its territories." Then came a number of statements asserting that Ethiopia has the right to execute any plans or projects necessary for its economy or to meet its water, agriculture, and power needs. To assert the seriousness of this stand, it enlisted those objectives in a letter addressed to all the diplomatic missions in Cairo [70, 71].

With news that Egypt sought to establish the AHD by submitting the project draft to the World Bank accompanied by Egypt's attempt to hold an agreement with Sudan, the Ethiopian government sent a memorandum to the United Nations declaring that it no longer recognize any of the historical Agreements of the Nile Basin. It also demanded to be a third party in the negotiations that were held between the Egyptian and the Sudanese sides. Reaching an agreement between the Egyptian and the Sudanese sides concerning the division of the Nile water in 1959, Ethiopia objected to this Agreement and questioned its international legitimacy. The reason was that Ethiopia considered that the Egyptian-Sudanese Agreement did not include all the international parties concerned with the water issue in the Nile Basin, which means that the Agreement was legally deficient [72].

At the same time, Ethiopia adopted a political campaign to incite the Nile Basin countries to reject the historic Nile Agreements. The pretext was that they were inherited colonial Agreements, even though the majority of these Agreements demarcate the borders between the Nile Basin countries, in addition to other African countries, and which and been ratified and accepted by the Organization of African Unity (currently the African Union) [6].

Ethiopia's incitement campaign was actually strong. Once the Nile Basin countries gained independence, they declared all Nile water Agreements as null and void, particularly the 1929 and 1959 Agreements. In turn, Ethiopia presented a memorandum expressing opposition to the two Agreements. On the same vein, Tanzania – accompanied by both Kenya and Uganda – declared the "Nyerere Principle" which rejected all Agreements signed in the colonial era [73].

Ethiopia's argument in that refusal was that the international law does not accept the notion of acquired rights for a State on an international river and that the 1959 Agreement did not distribute the waters of the Nile equitably to all the States of the Basin. Consequently, Ethiopia was not bound by it [74].

Ethiopia stressed that Egypt was required to notify the Nile States of the establishment of the AHD, as Ethiopia and the Nile upstream countries stressed the necessity to adhere to the "reciprocal" application of the requirement of "prior notification." This means that it refused to comply with the "prior notification" condition unless Egypt and Sudan complied. Hence, Ethiopia – leader of the upstream countries – demanded a "bilateral commitment" to the "prior notification" principle on the part of the upstream and downstream countries prior to the implementation of any regional water projects [75].

In this context, Ethiopia agreed with the United States (US Bureau of Land Reclamation) to carry out an overall study of agricultural and power generation projects that can be implemented in the Nile Basin in Ethiopia. When the United States withdrew its offer to finance the AHD in 1965, it claimed that this was due to the absence of a comprehensive agreement between Egypt and the upstream Nile countries. Thus, it is clear that the Nile was a source for the political conflict among the superpowers [76].

Naturally, Egypt and Ethiopia were part of this conflict, and that led to bad relations between the two states. According to Egypt's Nasser, Ethiopia was a hostile State especially after it signed a military Agreement with the United States in 1953 and received an Israeli general consulate to Addis Ababa in 1965. As a reaction, Egypt assisted the Eritrean separatists and backed Somalia during its conflict with Ethiopia. In addition, Egypt encouraged the "Grand Somalia" notion in order to weaken the Ethiopian front and ban it from using the Nile to pressure the Egyptian policies [77].

In addition to what mentioned above, in many regional and international forums, Ethiopia has denounced Egypt, its policy and the AHD project emphasizing that it was directed against it and against its progress [78].

However, the Ethiopian side had overlooked a number of facts [7]:

1. The feasibility studies of the AHD project proved that its benefits were more than its damages and that its damages were limited to Egypt and Sudan, the downstream countries. This means that it did not violate the principle of "no harm" under the international law.
2. Egypt had notified Sudan prior to the implementation of the dam, in accordance with the principle of "prior notification." The two countries had reached an understanding on all the issues related to the AHD.

The Ethiopian stance against the AHD can be explained in the light of the hydropolitical complexities between Egypt and Ethiopia since the 1950s, as well as Ethiopia's desire to build a number of dams on the Blue Nile waters according to the American plan since the 1960s. The aim was to realize the dream of hydropolitical hegemony over the Nile Basin and the Horn of Africa [79].

5.1.3 Other Nile Basin Countries Stance

The reactions of these countries ranged from opposition to moderation. At the top of the countries that sided with Ethiopia were Tanzania and Kenya, while other countries such as Uganda, Rwanda, and Eritrea adopted more moderate and less severe positions. It is notable that the position taken by these countries was due to the joint projects that bring them together with Egypt. Therefore, they were more keen on mutual cooperation with the Egyptian side [80].

5.2 International Stances

The international reactions can be divided into two groups. The first is the reaction of the Western bloc countries, namely, the World Bank, the United States, and a number of European countries, led by Britain, and second the reaction of the Eastern bloc countries led by the Soviet Union.

5.2.1 Western Bloc Stance

There was a real Western effort to exploit the AHD funding to impose a number of political demands on Egypt. This was known as the political conditionality, where there was a real refusal to finance the dam fully, and moreover, the financing of the dam was linked at one stage with subduing the Nile River to an international administration of which the Western bloc should have the upper hand [81].

The British Stance

When Egypt proposed the AHD project to store the Nile flood water in Aswan, there was an instant British reaction. There was an exchange of views between the English officials such as the Egyptian irrigation consultant, the English ambassador to Egypt, the Sudanese government agent in Cairo, the general governor of Sudan and the irrigation consultants there, and the Foreign Affairs Officer in London on this great project. The correspondents exchanged included many opinions and ideas. The English officials were of the opinion that the project should be rejected. They focused only on some of the disadvantages that may be caused by the construction of the dam, such as the seizure of large quantities of silt in times of flood, depriving agricultural lands of their benefits, and the negative disadvantages of the dam on Sudan. They considered the project as no suitable alternative to the major water storage projects that had been planned by British experts on the Nile's branches and sources.

The British Foreign Affairs Minister raised some questions about the Sudanese government's position on the idea of establishing the project as to what extent was the potential impact on the irrigation of Sudan, how would the Nile water be divided between Egypt and Sudan, and how much compensation would be paid by Egypt to the people of the Halfa region, and who would leave their villages because of a lake Dam. It was obvious that such inquiry was an attempt to set up a crack between Egypt and Sudan [82].

The negative impressions of the dam are evident from a letter from one of the English officials in Khartoum to the British Foreign Office, in which he says:

> The proposed AHD project in Aswan is not the suitable method to achieve this purpose. But rather, the full use of the Nile water should be achieved through establishing a number of dams along the river course [83].

The American Stance

In the light of the ideological rapprochement between the United States and Ethiopia during the reign of Emperor “Haile Selassie,” and in the light of the American hostility toward Nasserite Egypt, the United States withdrew its offer of financing of the AHD in July 1956. This was under the pretext that Egypt failed to conclude a comprehensive agreement on the AHD with the Nile upstream countries.

It was also noticed that after Egypt had begun the construction of the AHD with the help of the Soviets, the United States became interested in developing the Blue Nile in Ethiopia. In 1957, the US Bureau of Land Reclamation approved a detailed study, which ended in 1963, in favor of the Ethiopian government. The results of this study were then published in 17 volumes in 1964 [84, 85].

In some researchers’ opinion, it was not coincidental that the American study period of these projects coincided with the period of increasing tension between Washington and Cairo, especially under “Nasser’s” strengthening of the Egyptian-Soviet relations economically and militarily. Therefore, the US Bureau of Reclamation study was an apparent warning to Egypt of the possibility of being subjected to geopolitical pressure by the American – Israeli – Ethiopian tripartite alliance [86].

But since there was full coordination between Britain and the United States, the latter changed its position as a result of Britain’s insistence that the approval of the dam should be linked to the end of the bilateral rule in Sudan and the idea of postponing the evacuation of the British forces from the Suez Canal base. Britain also insisted that this approval should be linked to putting pressure on Egypt to join a US-British defense organization for the Middle East to encircle the Soviet Union [87].

Under the coordination between Britain and the United States, the latter confirmed in a secret letter sent to the British Foreign Office on December 8, 1953, by the Secretary of State, “Dulles,” that the United States would postpone its economic assistance to Egypt – including the financing of the AHD – until the new year 1954 [88].

The positions of the two great Western countries, the United States and Britain, were mixed, and they did not reach a final decision on the issue of financing the AHD. Then, an extended meeting was held at the State Department in Washington on November 29, 1955, where a large number of officials involved in the financing and construction of this dam – according to the British documents – attended and discussed the problems related to the construction and financing of the AHD. The meeting was attended by Sir Roger Makins, British Ambassador to Washington; Herbert Hoover, US Under Secretary of State; Randolph Burgess from the US Treasury; Mr. Eugene Black, President of the World Bank; Garner from the same bank; and Dr. Abdel Moneim al-Qaisuni, Egyptian Minister of Finance, and General Hilmi from the Egyptian government [89].

A telegraph sent from Washington to the British Foreign Office said that Egypt would still have a deficit in financing AHD – despite loans from the World Bank and the US and British governments – which would force the Egyptian government to borrow from abroad. Therefore, the British and US governments declare that any attempt by Egypt to borrow from other countries – namely, the Soviet Union – would prompt the two governments to reduce the number of their contributions to the project or to reconsider the overall lending process [90].

In this regard, "Dulles," US Secretary of State, met Egyptian Ambassador Ahmed Hassanein in the presence of Herbert Hoover, US undersecretary of state for the Middle East affairs. In this meeting, the Egyptian ambassador told Dulles that "He was worried about the Soviet offers and what they could provoke, mentioning that the United States must offer its consent to build the dam as soon as possible." Dulles responded: "We had seriously discussed this issue and appreciate its importance but frankly our economic position makes it difficult for us to participate in this project and so we withdraw our offer." At the moment Ambassador Ahmed Hussein entered Dulles' office, the US State Department spokesman distributed a statement to reporters announcing that the US offer to fund the AHD was withdrawn on July 19, 1956 [91].

It is clear that Britain and the United States were opposed to the AHD project from the beginning and tried to put pressure Egypt by pushing Sudan and the rest of the Nile Basin countries to reject the project by steering newspapers and radio stations to propagate the idea of rejecting the project.

Western Bloc Countries Competition Over the AHD Construction Contracts

The British documents show that Britain and the United States wanted to acquire the loan contracts to be granted to Egypt and the contracts of the companies that would be in charge of the construction of the dam because of their great material and political benefits. One of the evidences is that the meeting that took place in Washington between the World Bank and representatives of the Egyptian government concerning this project in November 1955 was attended only by representatives of the American and British sides and was not attended by any party of the French and German sides, who questioned the secret of ignoring them in those negotiations [89].

The French government was looking forward to having a role in the financing and construction of the project. The French Ambassador to the United States M. Chassepot said in an interview with officials at the English Embassy in Washington: "It would be a great opportunity for the French government if it took part in the financing of the AHD, and that it was ready if asked to play this role" [92].

In general, the French side was dissatisfied with its ignoring in the initial preparations for the AHD project in November 1955.The Germans were not less resentful than the French for not being involved in the dam contracts that might go to the Americans and the English only, although the German company – Hochtief – was the one that carried out most of the research and studies of the project [93].

Consequently, the French and German parties informed the British that they would withdraw from the Consortium – the French-German Companies Union – and consider it as invalid if the AHD construction contract was not discussed with each of them so that they would have the opportunity to participate in its construction [94]. On December 12, 1955, the British Foreign Office warned in a note of the danger of ignoring the French and the Germans in the talks concerning the AHD building contracts. The note emphasized that "This was against the integrity of the Western bloc, and may lead to the two countries to moving away from cooperating with us" [95].

5.2.2 Eastern Bloc Stance

The Soviet Union joined the international conflict over the AHD after Nasser declared the closure of the Suez Canal in 1956. The Czechoslovakian government mediation at that time facilitated communication between the Egyptian and Soviet sides resulting in the Soviet Union arming the Egyptian army in addition to signing an Egyptian-Soviet arms deal prior to that [81].

The Soviet Union had announced the possibility of funding the project of the High Dam when the Western bloc was hesitant to finance it. Egypt began to take serious steps to study the Soviet offer. After short negotiations, the Soviets agreed on the conditions put forward by the two sides. Egypt signed a financing agreement for the first phase Of the AHD project later on December 27, 1958. The agreement stipulated that the Soviet Union would provide Egypt with a loan of 400 million rubles, or about 34.8 million Egyptian pounds, which would be used to import machinery, equipment, and equipment not available in Egypt and to cover the expenses of Soviet specialists and technicians in carrying out the work of this stage [96].

On January 15, 1960, the first explosion was carried out at the site of switching the Nile water, thus announcing the start of the AHD first phase implementation. On January 15, 1960, the Soviet Minister Novikov in Cairo told 150 journalists and correspondents of news agencies and foreign newspapers that the Russian experts proposed to reduce the duration of the first phase implementation of the dam construction. He also announced that the Soviet Union welcomed any desire expressed by Egypt to finance the second and final stage of the construction of the project and that Egypt alone which could decide whether the Soviet Union could participate with the West in financing the second stage or not.

The Soviet leader, Nikita Khrushchev, ended all Western bets to participate in financing the AHD project on January 15, 1960, when he sent a letter to Nasser confirming the Soviet

Union's readiness to cooperate with Egypt in completing the second phase of the AHD. The message said:

> The construction of the AHD, which was the dream of generations of the Egyptians, has come to play an important role in achieving this end. During your conversation with our minister, A.T. Novikov, you officially expressed the desire of the government of the United Arab Republic (Egypt) regarding the involvement of the Soviet Union in building the second phase of AHD. The government of the Soviet Union, which has studied your wish, declares its consent to participate in the establishment of the second phase of the project on the same bases on which we agreed in the first phase [97].

On January 17, 1960, "Nasser" replied to "Khrushchev" with a message saying:

> We are delighted that you have agreed to participate in the establishment of the second phase of the AHD on the same bases as previously agreed when you participated in the first phase of the construction of this dam [98].

On August 27, 1960, an agreement was reached between the Soviet Union and the United Arab Republic (Egypt) regarding the completion of the AHD. It said:

> In accordance with what was agreed upon in the letters exchanged on January 15, 1960 between the President of the United Arab Republic and the Prime Minister of the Soviet Union regarding the contribution to the completion of the construction of the AHD, it was agreed to complete the establishment of the AHD and the final works associated with it [99].

6 Conclusion

The political circumstances that accompanied the call for the establishment of the AHD were very complicated because of the historical phase that Egypt experienced at the local and international levels. At the local level, Egypt was witnessing a transition era in its political history by moving from the monarchy to the republican system, in addition to the ending of the Egyptian dependence on the British. On the international level, that period witnessed the crystallization of the bipolar system and the escalation of the bipolar conflict with the accompanying complexities of the international political interactions.

It was clear that the international context was the determining factor in influencing the political and legal dimensions of the AHD in Aswan.

Politically, the dam had been politicized by the scientific, political, legal, and economic controversy raised about it, in addition to the political conditionality associated with its funding process.

In spite of these critical historical circumstances, they contributed in one way or another to the completing of the construction of that national project. At the domestic level, Nasser was able to mobilize the masses to overcome the internal complexities. As for the external obstacles associated with providing the required funding for the dam, the AHD was one of the areas of political conflict between the Western and Eastern camps in the Cold War era.

There was a Western effort (the United States-the United Kingdom-World Bank) to exploit the financing of the project to impose a number of political demands on Egypt. This was known as the political conditionality, where there was absolute refusal to finance the dam fully.

In fact, Egypt's refusal to yield to the demands of the US and British governments to stop dealing with the Soviets or to import arms from them, and its refusal to accept peace with Israel or to join the Middle East Defense Organization (MEDO) against the Soviets, was the main reason for the World Bank and the US and British governments to withdraw their financing of the AHD on July 19, 1956.

This was followed by Britain, France, and Israel's declaration of war on Egypt, leading to the internationalization of the AHD case. With the World Bank and Western donors withdrawing from funding the dam, the Soviet Union entered into negotiations with Egypt to provide technical and financial assistance to build the AHD. The Soviets had no reservations because of the enormous economic advantages of the project, and they had no doubts about Egypt's economic and financial ability to complete the project and face its financial burden.

The Soviet Union emerged on the political struggle scene over the AHD and provided Egypt with political, financial, and technical support which enabled Egypt to build the AHD without succumbing to the Western political conditionality.

Thus, the international bipolar system helped attract as many international allies as possible. This enabled Egypt to obtain the necessary funding from the Soviet Union after the Western side, represented by the United States and Britain, refused to finance the dam. This means that the political obstacles – domestic and international – that faced the Egyptian regime were overcome.

As for the legal dimensions of the Aswan AHD, despite the fact that Britain, the United States and Ethiopia raised several legal problems, yet the AHD was consistent with the principles contained in the general international law of the international rivers. It is notable that among the legal problems raised against the AHD was the call for the necessity of Egypt's consultation with the other Nile Basin countries. In addition, Egypt also faced the Ethiopian initiative to submit a formal protest note to the United Nations for building the dam without prior consultation. Another controversial issue was raised concerning the eligibility of the revolutionary coup government in Egypt to sign funding agreements with donors to finance the dam. Moreover, another argument was raised about the economic feasibility of the AHD project compared to the damage that may result. Hence, another controversial issue was raised concerning the "significant harm" that may result from the AHD. Nevertheless, the AHD was consistent with such principles of "no harm," "respecting acquired rights," "prior notification," "international cooperation," "fair and equitable utilization," "peaceful settlement of disputes," "non-abuse of the right," and "good neighborliness."

Egypt had complied with the "prior notification" condition prior to the construction of the AHD, as it notified Sudan and discussed with it all the water, environmental, engineering, and financial issues related to the AHD and its potential impacts.

Egypt had also adhered to the principle of "no harm" when establishing the AHD, as it did not affect the amount or quality of water flowing in the course of the Nile. It did not also pollute the river nor did it affect current and future water uses of the upstream countries. The AHD does not also constitute an obstacle to any of the Nile countries to use the water and resources of the Nile River. This confirms the consistency of the AHD and the principle of “not causing harm.”

In the field of water cooperation, the dam represented a model of cooperation between riparian countries in international rivers, where an understanding between Egypt and Sudan on issues related to the dam was achieved and codified in the “Convention of the full use of the Nile water” in 1959.

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Continuous Dispute Between Egypt and Ethiopia Concerning Nile Water and Mega Dams

Nader Noureldeen Mohamed

Contents

Abstract This chapter discusses the continuous dispute between Egypt and Ethiopia within the last 100 years concerning the use of Nile water and the building of mega dams. The one-sided decision by Ethiopia to construct the Grand Ethiopian Renaissance Dam (GERD), a mega dam, exploited Egyptian circumstances after the January 2011 revolution by announcing the construction of what will be the biggest dam in Africa and one of the ten biggest dams in the world, a dam that will profoundly harm Egypt. With that announcement, and the previous recent history of Ethiopia in aligning some upstream countries against Egypt to sign the Entebbe agreement, in May 2010, a deep dispute has begun between Egypt and Ethiopia.

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Egypt believes in the use of the total water resources of the Nile Basin, while the upstream countries believe only in using the water stream that flows between the white river banks. The Entebbe agreement, or the “Nile River Basin Cooperation,” which was signed by six upstream countries, was the first step in the current broad breach between Egypt, Ethiopia, and most countries of the White Nile Basin. The Agreement considers that the history of Nile treaties and agreements began in 2010, canceling all former agreements or treaties. Egypt has suggested building on this Agreement by cooperating in collective work to control the huge water losses in the upstream swamps, wetlands, and on the shores of the upstream lakes, a process which could increase the river discharge by another 100 billion cubic meters, to be shared by all the riparian countries. The upstream countries claim absolute territorial sovereignty over the river water and its tributaries, while Egypt seeks absolute territorial integrity, as outlined in the 1997 United Nations (UN) river water law “Convention on the Law of the Non-navigational Uses of International Watercourses”, which describes and locates the relationships between riparian countries. Some countries, such as Ethiopia, claim that Egypt prevents them from producing food for their people, while in reality, of the Nile riparian countries, Egypt has the least agricultural land area (3.5 million ha), while Ethiopia has 35 million ha, Tanzania has 50 million ha, Sudan has 83 million ha, and Kenya has 33 million ha. The area under cultivation for biofuel crops in Ethiopia exceeds all of Egypt’s agricultural land by twofold. The policy of some upstream countries has been to turn to biofuel instead of food and to suggest that other countries are doing the same. The Ugandan parliament has called for Egypt to pay for Nile water that Egypt has rights to. All these issues and others will be discussed in this chapter to highlight and confirm the specific water rights that Egypt has in regard to Nile water, and to stress that these water rights should not be affected by any other upstream countries. On the other hand, Egypt can support the upstream Nile Basin countries to achieve their water and hydropower development projects unless these projects cause harm to Egypt and its Nile water share.

Keywords Dispute, Egypt, Entebbe, Ethiopia, GERD, Mega dams, Nile Basin, Sudan, Upstream

1 Introduction

The Blue Nile originates at Lake Tana, 1,830 m above sea level in the Ethiopian Highlands, where the average annual rainfall is high and evaporation is relatively low. The river gathers more than 20 tributaries between Lake Tana and Khartoum, including the Rahad, Didessa, Dabus, and Dinder Rivers [1, 2]. The Blue Nile supplies a total discharge of 5 billion cubic meters (BCM). However, many added tributaries increase its total discharge to 48.85 BCM; in addition another 5 BCM comes from the Rahad and Dinder Rivers, both of which join the Blue Nile from Sudan [2–4], as seen in Fig. 1. The Blue Nile extends for 850 km to reach the Sudanese border, with a downhill slope of 1,300 m. However, when it reaches the Roseires Dam (80 km into Sudan) it begins to lose more water from evaporation than

Fig. 1 Ethiopian Nile River Basins: Blue Nile, Atbarah and Sobat, and their tributaries [3]

it receives in rainfall. The Blue Nile provides an average of 59–64% of the Nile's flow at Khartoum, the capital of Sudan, where it joins the united Nile. Additional inflow from the Ethiopian highlands comes through the Atbarah River, which enters the Nile 330 km north of Khartoum downstream. Figure 1 shows the Nile Basin catchment areas in Ethiopia.

2 Blue Nile Journey from Lake Tana to Khartoum

The climate of the Ethiopian highlands and Lake Tana varies significantly from the climate of the lowlands near the border with Sudan. Lake Tana is 1,830 m above sea level and receives an annual average precipitation of 936 mm. Most of the highlands of Ethiopia, at elevations between 1,500 and 3,000 m, are wet, lush, and green, and have daily mean temperatures ranging between 15 and 18°C. As the Blue Nile descends to the lowlands of the border with Sudan, rainfall decreases and temperatures increase, reaching substantially higher levels than those at Lake Tana; evaporation thus increases, resulting in a significant net loss of water. In the region of the Sennar Dam, located in eastern Sudan close to the Ethiopian border, evaporation rates increase to 2,500 mm per year, compared with the rate of 1,150 mm per year in the highlands, while the annual rainfall is only 500 mm and the mean daily temperature is 30°C [5]. Monthly precipitation also varies substantially between the highlands and lowlands. In east Sudan rainfall in the summer monsoon season (June–September) [6, 7] accounts for nearly 90% of the total annual precipitation; on the other hand, in the Ethiopian highlands, almost 75% of the annual precipitation falls during the monsoon season [8–11].

3 River Flows in the Ethiopian Nile Basin

The collective water discharge coefficient of the Nile is only 3.9%, which is very low compared with that of most rivers in the world [3]. The main source of the Nile River is in the Ethiopian highlands, with a total share of the main Nile water of 85–86% (72–73 BCM/year), while the equatorial lake region source represents only 14–15% of the total share of the main Nile water (12–13 BCM/year) [12, 13]. The sources of the White Nile are the lakes of the Equatorial Lakes Plateau, including Lakes Victoria, Kyoga, George, Edward, and Albert and some other small lakes. The sources in the Ethiopian highlands include the Blue Nile (59–64%), the Baro-Akobo (Sobat) River (14%), and the Takeze (Atbarah) (13%) [8, 13]. The White and Blue Nile meet in Khartoum, while the Atbarah River flows into the main Nile 330 km north of Khartoum, and the Nile continues its flow to Egypt. Tables 1, 2, and 3 show the areas and flows of the rivers upstream of the Nile.

Table 1 Nile Basin areas and flows [14]

Sub-basin	Area in km (%)	Flow in billion cubic meters; BCM (%) at Aswan, Egypt	Annual rainfall (mm)
Blue Nile	311,548 (17)	48.85–54 (59–64)	500–1,800
Bako-Akobo-Sabat	205,775 (11.5)	13.5 (16)	500–1,750
Takeze-Setite-Atbarah	227,128 (13)	12 (14)	200–1,500
Total Ethiopia sub-basin	744,451 (41.5)	72–73 (85–86)	1,200–5,050
White Nile	262,441 (14.4)	15 (18)	300–500
Main Nile total	789,660 (44)	84 (100)	0–200

Table 2 Potential rainfall volumes in Nile River sub-basins [15]

	Sub-basin	Area (km^2)	Mean annual rainfall (mm)	Rainfall volume (km^3)
1	Equatorial lakes	394.147	1,201	473
2	Bahr-El Ghazal	584.769	752	440
3	Blue Nile	298.383	1,017	304
4	Upper White Nile	234.181	1,004	235
5	Lower White Nile	256.041	514	132
6	Takeze-Atbarah-Setite	221.685	480	107
7	Main Nile above Dongola	389.106	116	45
8	Main Nile below Dongola	443.580	100	44
9	Total water discharge			1,977

Table 3 Mean annual flows of the Nile tributaries [14]

Name	Annual flow (km^3)
Nile at Aswan	84.1
Atbarah at mouth	11
Blue Nile at Khartoum	48.3
White Nile at Khartoum	26
Sobat at Malakal	9.9

4 Nile Basin and Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC) 2001, the total rainfall in the Nile Basin, especially in the Ethiopian basin, may increase by 30% or may decrease by 70% of the normal average by the year 2050 [16].

The east African countries Ethiopia, Kenya, and Tanzania are classified as highly vulnerable to climate change; particularly since they rely on agriculture to support their economies. These countries are characterized by a high percentage (80%) of their populations directly working in the agriculture sector, and this sector represents almost 40% of the total gross domestic product (GDP) [2, 3]. It is expected that climate change will have a significant impact on agricultural and water resources in these countries, and they need to plan and create policies to cope with and adapt to global warming to prevent the expected reductions in yields of essential crops, cash crops, and livestock. The expected frequent droughts and dryness will affect east Africa including the Nile Basin, causing chronic water scarcity, which may exacerbate conflicts and migration.

The Upper Blue Nile Basin occupies 17% of the area of Ethiopia (176,000 km^2 out of 1,100,000 km^2), and has a mean annual discharge of 48.85 BCM (1912–1997; 1,536 m^3s) [14]. The Blue Nile has only one significant waterfall, at the TisIsat cataract, roughly 25 km from Lake Tana, where the river drops 50 m into a deep gorge. Much of the highland plateau is above 1,500 m and consists of rolling ridges and flat grassland meadows with meandering streams that lead to waterfalls over the vertical sides of canyons.

According to Mostafa et al. [14], the construction of ten dams on the eastern Nile would reduce average annual water discharge, also increasing evaporation and reducing energy production at the Aswan High Dam by 18%, and 4%, respectively. This may cause the Lake to dry out. The average annual total water received at the Aswan High Dam may also be severely reduced owing to climate change, by 24%, 35%, and 36% for the near future (2011–2040), intermediate future (2041–2070), and far future (2071–2100), respectively [14], and the average annual evaporation would increase from 4% at present to 29%, 62%, and 63% for the near future, intermediate future, and far future, respectively. Increased evaporation losses would lead to increases in Nile water salinity and pollution caused by the increased presence of concentrates. Moreover, the energy production at the Aswan High Dam would decrease by 12%, 28%, and 29% for the near future, intermediate future, and far future, respectively (Fig. 2).

Egypt should plan new policies to cope with and mitigate the impact of climate change; for example:

- Change the current flooding irrigation system to scarcity systems such as sprinkler and drip irrigation.
- Increase the use of reclaimed and treated wastewater, such as agricultural drainage water, for irrigation and industrial purposes; create future policies for harvesting rainwater that is now lost in desert areas; and establish uses for desalinated seawater and desalinated brackish water.
- Use better control systems with tight gates (has no seepage or leaking) which control the water discharge on irrigation canal.
- Increase the efficiency of water delivery systems by changing the systems to cement or closed pipe systems.
- Increase general awareness of people and farmer by the importance of the need for these measures.

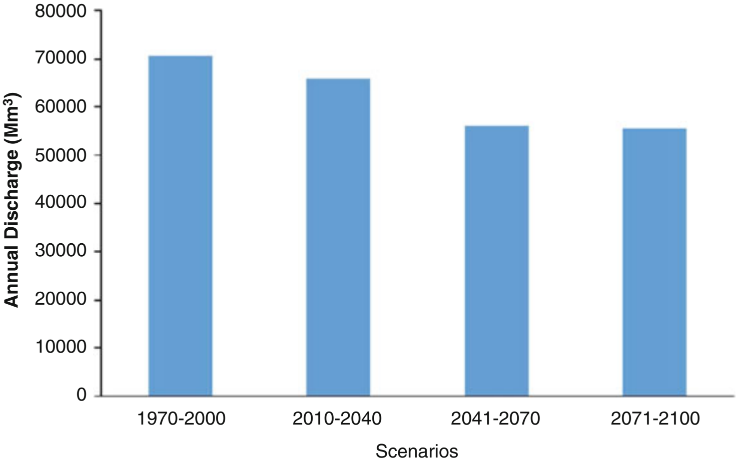


Fig. 2 Annual precipitation in the Nile Basin under different climate scenarios [14]

A study by the Strategic Foresight Group [17] reported on the average flow of the Nile River within the last 150 years, which was 42 BCM at its minimum (1913–1914), and 150 BCM at its maximum (1878–1879), with a mean annual flow from 1900 to 2004 of 85.31 BCM. Climate change models predict increases or decreases of 15–20% in annual precipitation. Climate change in the Nile Basin, which will mainly affect the agriculture sector, could lead to a decline in yield by up to 50% in Ethiopia, Kenya, Tanzania, Uganda, and Sudan. It is expected that the temperature across the Nile Basin will increase by 1.5–2.1% by 2050, which means that almost the entire Nile region may become an arid to semiarid region within the next 30–40 years. This could significantly reduce the amount of agricultural land [17].

The study by the Strategic Foresight Group in 2013 titled "Blue Peace of the Nile" [17] concluded that the impact of climate change would affect water flows and water quality and then reduce food security in the region. Food insecurity in the region is expected to increase in the next 30–40 years, owing to a projected drop in agricultural productivity by up to 50%, which is expected to be caused by rising temperatures, climate change, drought, and the rainy season times being reduced to narrow and intense periods. These factors could also lead to a 30–50% drop in food production. In the next 30–40 years, the population of the Nile Basin is expected to double. Figure 3 shows the projected impact of climate change on the Nile Basin in the period 2007–2040.

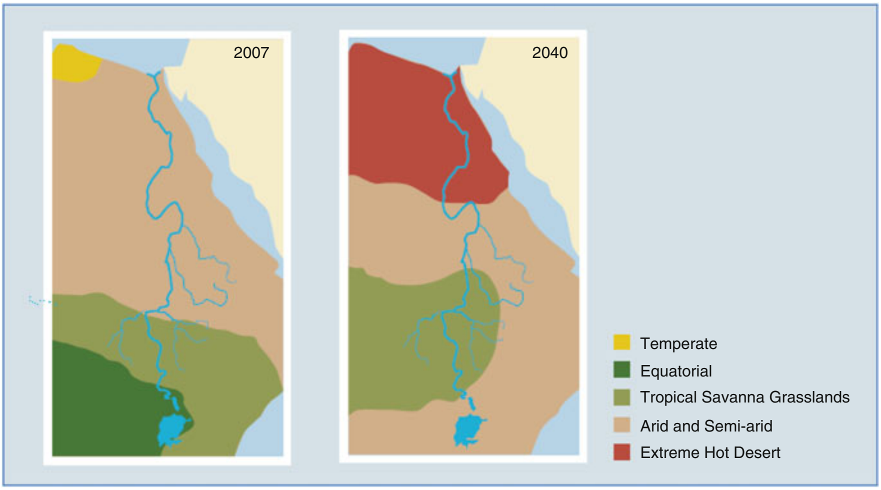


Fig. 3 Climate change in the Nile River Basin [17]

5 Reasons for Disputes Between Egypt and Upstream Countries

5.1 High Losses of Fresh Water in Upstream Countries

As mentioned before, the collective water discharge coefficient of the Nile is only 3.9%, which is very low compared with that of great rivers elsewhere in the world [3, 12, 13]. As seen in Table 2, the potential total rainfall in the water catchment areas of the river reached 1,977 BCM, but only 84 BCM of this great amount drained into the river stream itself between its two banks. The amount of water that actually goes into the stream represents only 4.2% of the total water in rainfall the Nile Basin receives. This means that the Nile River loses most of its water; this occurs through several swamps and wetland areas adjacent to the Nile Basin lakes. For example, the Sudd swamps in the South Sudan lose 30 BCM/year, in addition to the loss in the Machar, Bahr El-Arab, and Bahr El-Ghazal swamps [18]. Thus, although the river Nile is really the longest river in the world, it is small in terms of its water discharge. We can state that the river Nile is an almost empty river compared with the Amazon River, which has a total water discharge of 5,500 BCM; or the Congo River, with a total water discharge of 1,284 BCM; the Mississippi, with a total water discharge of 562 BCM; or even the Zambezi, with a total water discharge of 223 BCM [2]. Conflicts are expected between the Nile Basin countries because of the small amount of water in the river and because of the high population growth rate in all the Basin countries, which reached a total of 378 million in 2010, with growth predicted to reach double that total in 2050 [3]. The only way to solve this problem is to cooperate in taming (collecting) the water loss in the swamps and wetlands around Lakes Victoria, Kyoga, and Albert, in addition to resolving the water loss in the Sudd, Mashar, Bahr El-Ghazal, and Bahr El-Arab swamps in South Sudan. Figure 4 (from a to f) shows the loss of water in the swamps and catchment areas.

5.2 Entebbe Agreement 2010

On May 14 2010, the Nile Basin Cooperative Framework Agreement, well-known as the Entebbe Agreement [19], was signed, and stated that all swamps owned by upstream countries were to be under the absolute sovereignty of each country, and each sovereign country was to be responsible for taking special care with the Agreement's rules on the environment and biodiversity (Fig. 4). The Agreement considered that the history of Nile River agreements and treaties was just beginning in 2010, and it canceled all previous Nile agreements and treaties, considering this Agreement to represent the end of Egyptian hydro-political hegemony [19, 20], thus preventing any solely Egyptian effort to make plans and cooperate in the collection or taming of the swamp water upstream. Egypt understands that we should build on the last Agreement and treaty such as (1902, 1929, and 1959) and cooperate in

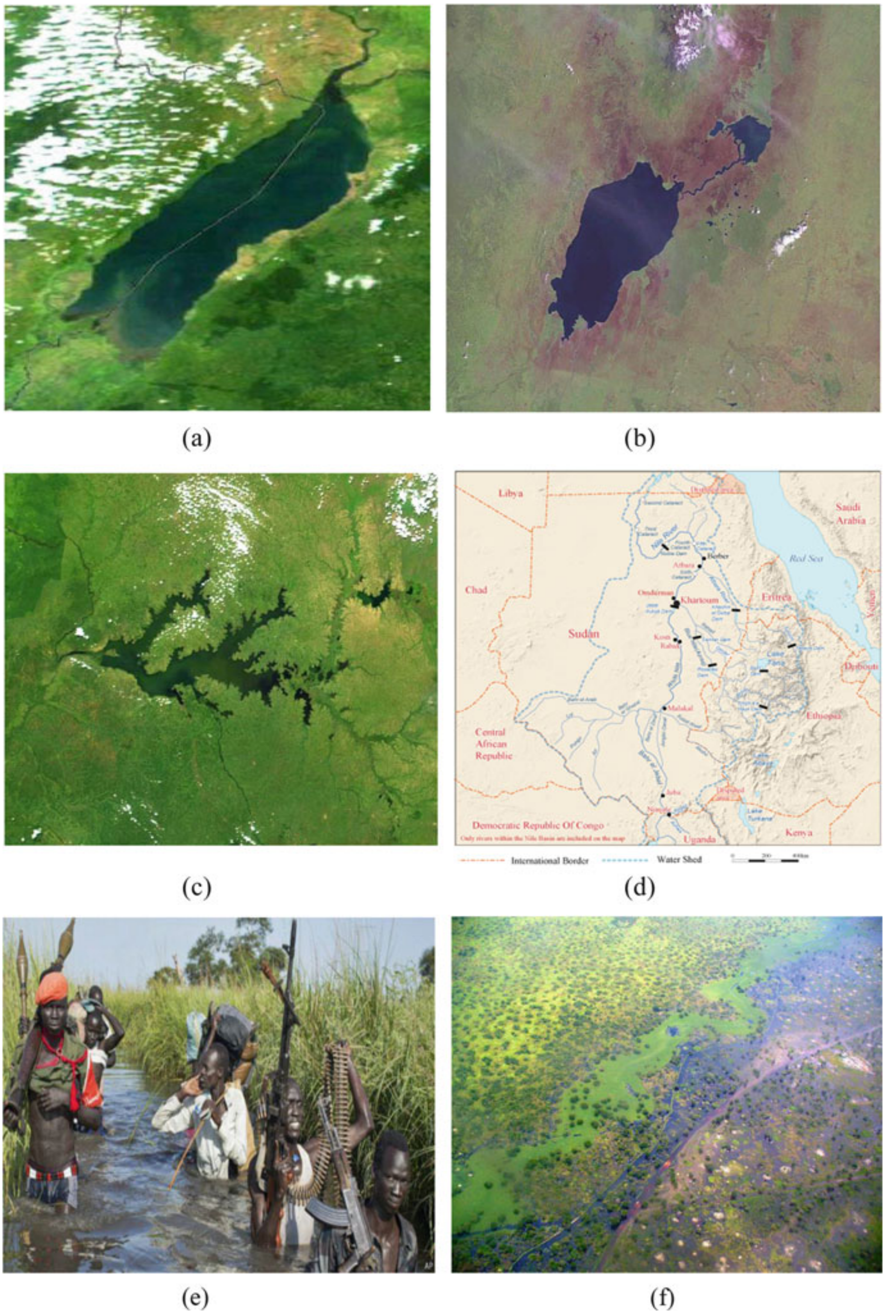


Fig. 4 Wetlands and swamps in some equatorial sub-basin lakes: (**a**) wetlands around Albert Lake, (**b**) wetlands around Lake George, (**c**): wetlands around Lake Kyoga, (**d**) map of Sudd swamp South Sudan, (**e** and **f**) General view of Sudd swamp

collective works to tame and aggregate the swamp and wetlands water to increase the total stock of Nile River water discharge; then all Nile Basin countries could reap the benefit and gain shares of this added water, which could reach 100 BCM. However, the Agreement gives ownership of the swamps to the countries that they are located in, and this will prevent any Egyptian effort to obtain useful results from this swamp water, placing this water under the absolute hegemony of the upstream countries only. The Agreement also uses unclear, non-specific, and controversial terms, such as "significant hazard", when talking about Egypt's share of the water and redistribution of water shares in regard to the shares of upstream countries. This vague term does not clarify who has the responsibility to calibrate what is "significant". For example, would water share decreases from Egypt be considered a "significant hazard" when Egypt's water shares decrease by 3, 5, 10, or 20 BCM a year? The United Nations (UN) water law of 1997 (Convention on the Law of the Non-navigational Uses of International Watercourses 1997) [24] does not give the upstream countries the sole right to determine the quantification of downstream countries' water share. In the case of an Egyptian population of 93 million with a total water resource of 62 BCM/year (55.5 Nile + 5.5 ground water + 1.3 precipitation) [22], with a water share of 666 m/capita below the water scarcity level and close to acute water scarcity, the lowering of Egypt's water share by even 1 m^3 would be a significant hazard.

5.3 Arguments About the Concepts of Total Water Resource and Water Income

The differences in the distribution of Nile Basin water between Egypt, Sudan, and upstream (shown in Fig. 5) may explain the reason for the high sensitivities about this matter in the upstream and downstream countries. The upstream countries wonder because they contribute 95.5% of the water in the rainfall and catchment watershed area, compared with only 4.5% for Egypt and Sudan, whereas Egypt and Sudan take 90% of the Nile stream water compared with only 10% for the upstream countries Moreover, the total water resources in the upstream countries are 59.5% compared with 40.5% for Egypt and Sudan; while the renewable water in the upstream countries is 56% compared with 44% in Egypt and Sudan [23]. Thus, upstream countries feel deep injustice and they demand a greater water share for development requirements from the water that flows between the Nile's two banks, with no discussion of their renewable water resources such as heavy rain or ground water.

In contrast, Egypt and Sudan ask for another view to consider the total fresh water resources and the alternative water resources from other rivers in upstream and downstream countries. The total renewable water should include the total of rainfall, ground water, and surface water of rivers, tributaries, and lakes. These resources contribute efficiently to a country's GDP, especially contributing to rainfed

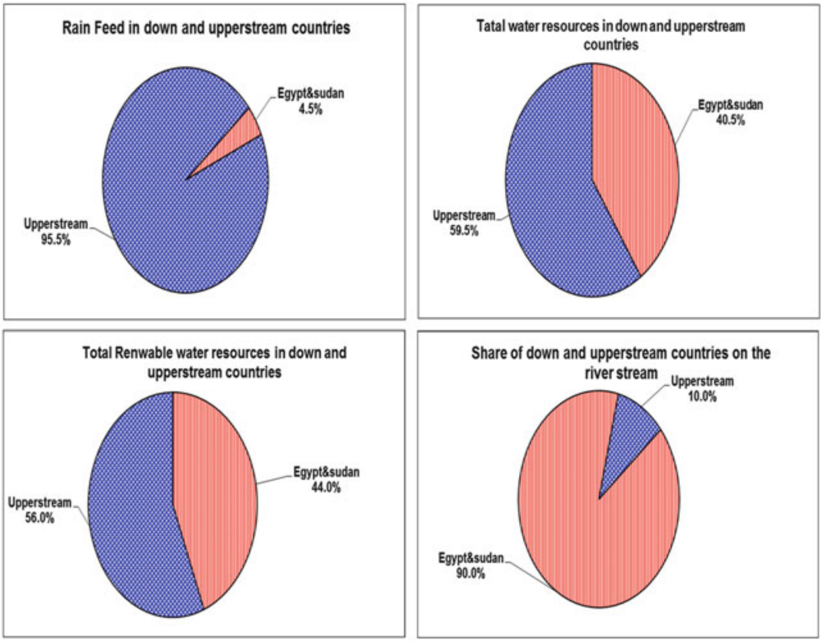


Fig. 5 Differences seen in Nile Basin water between Egypt, Sudan, and upstream countries (adapted from [23])

agriculture, organic farms, and livestock, as the UN water law (Convention on the Law of the Non-navigational Uses of International Watercourses 1997) states, as follows:

> *Article 7*
>
> *Obligation not to cause significant harm*
>
> 1. Watercourse States shall, in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States.
> 2. Where significant harm nevertheless is caused to another watercourse State, the States whose use causes such harm shall, in the absence of agreement to such use, take all appropriate measures, having due regard for the provisions of articles 5 and 6, in consultation with the affected State, to eliminate or mitigate such harm and, where appropriate, to discuss the question of compensation [21].

However, for example, Ethiopia owns Lake Tana entirely, with a high income from fishery and irrigation of the surrounding lands, accomplished with colossal rainfall that reached 936 BCM, according to the UN Food and Agriculture Organization (FAO) [24, according to 25]; this gives Ethiopia massive areas of pasture and a livestock population of 100 million head. Thus, Ethiopia has the most significant livestock population in Africa. The livestock subsector comprised 11% of national GDP and 24% of agriculture GDP between the years 1995/1996 and 2005/2006, and is a source of revenue for 60–70% of the population. According to the same reference, 80% of smallholder farmers own cattle, 31–32% own sheep, and 21–33% own goats. Table 4 shows the livestock population in Ethiopia, and Table 5 shows aspects of water resources and uses in Egypt and Ethiopia in 2007.

In contrast to the high Ethiopian livestock population, Egypt has only 8 million head. This low livestock population has led to Egypt being one of the biggest wheat-importing countries in the world. Egypt has no rainfall, and no natural pasture or forage. Thus, farmers are obliged to cultivate irrigated green forage crops such as alfalfa (clover) in winter and green maize grown as summer forage. However, these summer forage crops push Egypt to the number four position in the list of the biggest yellow maize-importing countries (80% of Egyptian needs) and it is the seventh largest importer of the edible oils of soy, sunflower, and palm oil. With all these pressures on the Egyptian agriculture system, governed by the small livestock population, Egypt also imports about 60% of its red meat, 10% of its poultry, 60% of its dairy butter and butter oil, and 70% of its milk powder. Thus, in Egypt, livestock represents an overload, causing high pressure on the economy. Agriculture represents only 12% of the Egyptian GDP although the sector consumes 85% of the

Table 4 Livestock population (thousand head) by region (2007/2008) in Ethiopia [24, according to 25]

Region	Cattle	Goats	Sheep	Region share of total livestock (%)
Tigray	3,119.4	3,005.5	1,388.1	7.4
Afar	1,627.2	3,398.2	1,799.0	6.8
Amhara	11,757.3	5,466.6	9,469.7	26.4
Oromiya	21,375.7	6,678.4	9,391.1	38.1
Somali	675.6	1,710.4	1,316.8	3.7
Benishangul Gumuz	363.6	371.5	85.3	0.8
SNNP	9,574.7	2,624.6	4,000.1	16.0
Gambella	212.6	54.6	48.1	0.3
Harari	40.8	41.2	5.0	0.1
Addis Ababa	89.5	19.1	21.8	0.1
Dire Dawa	49.8	154.7	59.6	0.3
Ethiopia total	48,886.2	24,526.9	27,584.6	100.0

SNNP Southern Nations, Nationalities, and People

Table 5 Aspects of water resources and water uses in Egypt and Ethiopia [24, according to 25]

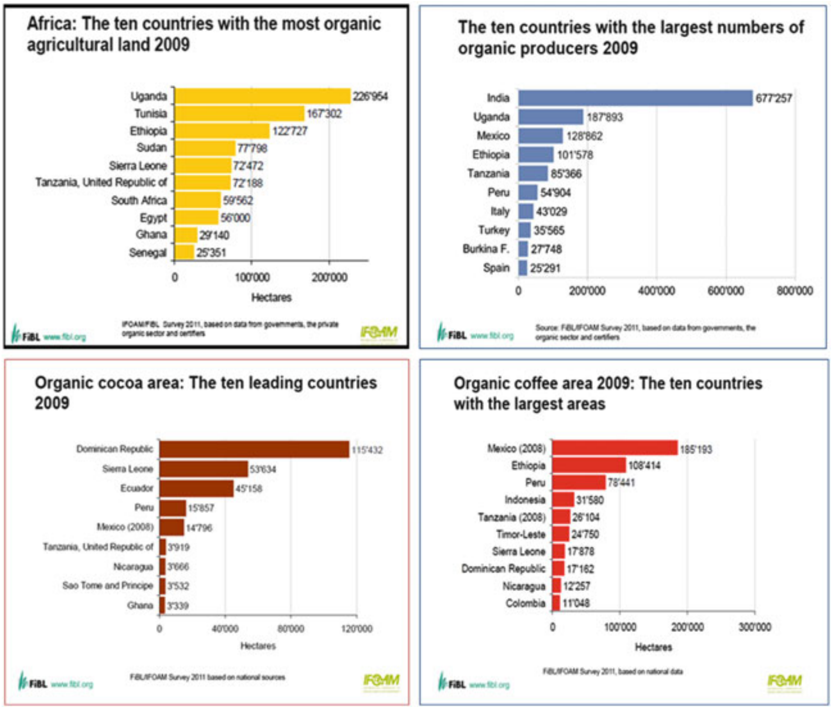
Aspect of water use	Egypt	Ethiopia
Average precipitation volume (BCM/year)	51.07	936.40
Total actual renewable water resources (km^3/year) actual/natural	57.3/85.8	122.00
Total annual water resources per capita (m^3/inhabitants/year)	702.80	1,512.00
Withdrawals of total actual renewable water resources (%)	117.20	5.1
Total annual renewable water resources withdrawn by agriculture (%)	103.00	4.3
Dependency ratio on the Nile water (5)	96.86	0.00
Irrigation potential (1,000 ha)	4,420.00	2,700.00
Area equipped for irrigation (1,000 ha)	3,422.00	290.00

total water resource and 103% of the Nile water share; indeed, Egypt is a net food-importing country. This point does not mean that Egypt has become an industrial country, with the industry share of GDP being 36%. Egypt still imports the modern technology needed for industry, which is mostly represented by small projects and small factories

Regarding rainfed agriculture and organic farms, upstream countries have an advanced position in exporting organic food and goods because of their high, intensive, and continuous rainfall during most months of the year. Egypt, with its deep lack of food security, is still far from this sector, even with its high relatively income with its high population (Egypt is the second high economic in Africa after South Africa, WB, Development Report 2016). Ethiopia, Uganda, and Tanzania are high producers of organic food and goods in Africa and worldwide, in addition to the high Kenyan tea production. Figure 6 shows the production of *some* organic food (tea and coffee) in addition to number of organic producers and large organic areas in Africa and worldwide.

Finally, in regard to water sharing, the UN water law (Convention on the Law of the Non-navigational Uses of International Watercourses 1997) [21] states:

1. Water income and its additional value should be taken into consideration instead of excluding green water (rain) or ground water and only discussing blue water (water stream in the river).



Africa: The ten countries with the most organic agricultural land 2009

IFOAM/FiBL Survey 2011, based on data from governments, the private organic sector and certifiers

The ten countries with the largest numbers of organic producers 2009

Source: FiBL/IFOAM Survey 2011, based on data from governments, the organic sector and certifiers

Organic cocoa area: The ten leading countries 2009

FiBL/IFOAM Survey 2011 based on national sources

Organic coffee area 2009: The ten countries with the largest areas

FiBL/IFOAM Survey 2011, based on national data

Fig. 6 Top organic food and tea-producing countries in Africa and worldwide [26–28]

2. The total water resources above and under the ground (green, blue, and gray), in addition to alternative, additional, and other water resources should be taken into consideration when we discuss more water shares for some countries.
3. The principle of “justice”, not “equality”, should be applied.

5.4 Oil Discovery in Lake Albert and the Surrounding Arable Lands

Lake Albert is 160 km long and 32 km wide, and is classified as Africa’s seventh largest lake. It forms part of the Uganda–Democratic Republic of Congo (DRC) border, with the two countries sharing the lake, with almost 51% to Uganda and 49% to the DRC [29, 30]. Most of the land around the lake is used for agriculture (crops and livestock) and the surrounding communities rely on the lake to provide fish and water.

Current oil exploration began in the late 1990s in Uganda, and increased in 2003–2004, with major finds confirmed in 2006 and 2007 [30].

On the DRC side, oil exploration is developing more slowly than in Uganda, although the DRC has been a minor producer of oil from other parts of the country since the mid-1970s.

It is estimated that oil exports could generate between 2 billion dollars and 5 billion dollars per annum for Uganda for more than 20 years, and the same for the DRC.

The conclusion of the last discussion is:

1. Upstream countries may cultivate large areas around Lake Albert, in addition to using the areas around Lake Victoria (35 million people live around this lake) and Lakes Edward, George, Kyoga, and Tana for livestock and fisheries, without any benefits to Egypt.
2. Oil discovery in Lake Albert will provide an annual income of between $US2 billion and $US5 billion for Uganda for more than 20 years, and the same for the Democratic Republic of Congo.
3. The total income from fisheries in Lake Victoria for the three countries Kenya, Tanzania, and Uganda reached US$219.4 million in 1998, from Nile Perch fish only [31, p. 119].
4. The only thing that Egypt gets from the River Nile is the water, without any lakes or tributaries; even regarding the fish, Egypt produces 75% of its requirements from aquafarming , with the rest produced from open fishing in the five Mediterranean lakes, as well as in the North Delta and lakes in Sinai.

5.5 *History of Problems and Political Violence (Altercations)*

For a long time Egypt has considered Ethiopia to be a trouble-making country. In the era of Mohamed Ali, the Egyptian "Wali" (president) (1805–1845), there was a war between Egypt and Ethiopia, which was waged for almost 80 years to protect the Sudan lands, because Ethiopia believed that their lands extended to Khartoum and to 330 km north of Khartoum where the Atbarah River meets the main Nile near the Egyptian border. A man of Ethiopian citizenship assassinated the elder son of Mohamed Ali, who led the Egyptian army in Sudan, and the assassin escaped to Ethiopia, but Ethiopia refused to extradite this person to be judged in Egypt [32].

In the colonial history of the Nile, the 1902 agreement between Ethiopia and the Sudan was the most controversial treaty, because the two parties ascribed different meanings to the treaty's provisions. The primary aim of this treaty was to delineate borders between Ethiopia and the Sudan. Article III of this treaty relates to the use of Nile water. The English version reads: "His Majesty the Emperor Menilik II, King of Kings of Ethiopia, engages himself towards the Government of His Britannic Majesty not to construct or allow to be constructed any work across the Blue Nile, Lake Tana, or the Sobat, which would arrest the flow of their waters except in agreement with his Britannic Majesty's Government and the Government of Sudan" [30]. Ethiopia claimed that, in Amharic, the meaning was that obstruction or blockage of the river was forbidden, but the use of the water was not. Ethiopia also claims never to have ratified the document.

This treaty was the first to engender disputes that threatened the socio-political and economic dynamics of the region, as well as future efforts toward cooperation [32].

This treaty was later denied by Ethiopia under claims that King Minilik "the second" did not send the treaty to the Ethiopian Parliament for accreditation. Later still, Ethiopia claimed that this treaty did not prevent Ethiopia from using the waters of the Blue Nile, rather than caring for the stream crossing their lands.

In 1959, before constructing the High Dam in Aswan, Egypt and Sudan signed an agreement for sharing the Nile water that had regularly arrived in Aswan over the past 100 years. Emperor Haile Selassie of Ethiopia (1942–1974) was much provoked and said: "One day Ethiopia will build dams across the Blue Nile that will make the Egyptian High Dam 'good for nothing' and become just a wall" (obtained from several readings in the Egyptian and international newspapers).

After the communist (socialist) coup in Ethiopia in 1977, the new president, Mengistu Haile Mariam, threatened Egypt that he would build a series of great dams over the Blue Nile without care for the Egyptian people. Anwar Sadat, the President of Egypt at that time, famously stated "We will not wait for death thirsts in Egypt but we will go to Ethiopia to die over there" (several readings in the Egyptian newspaper during the Egyptian President Anwar Sadat (1970–1981)) [33]. Mengistu withdrew his threat and later calmed down, but Sadat never forgot this threat and predicted that more trouble "as usual" may come from Ethiopia (several readings in the Egyptian and international press).

In 1979, President Anwar Sadat said: "The only matter that could take Egypt to war again is water" [23, 34]. In 1985, when Boutros Boutros-Ghali was Egypt's minister of state for foreign affairs, he was quoted as saying: “The next war in our region will be over water, not politics” [23, 35]. Emperor Haile Selassie had previously been quoted as saying: “We have already explained the plans under construction to utilize our rivers as an essential step in the development of agriculture and industry. This is of paramount importance to Ethiopia, a problem of first order that the waters of the Nile be made to serve the life and the needs of our beloved people, now living and those who will follow us in centuries to come. However, generally Ethiopia may be prepared to share this tremendous God-given wealth of hers with friendly nations neighboring upon her, for the life and welfare of their people. It is Ethiopia’s sacred duty to develop the great watershed which she possesses in the interests of her own rapidly expanding population and economy” [35].

In 2011, the elected Prime Minister of Ethiopia Meles Zenawi (1995–2012) exploited the January revolution in Egypt (which had displaced President Mubarak on 11 February 2011). Just 40 days after the displacement of President Mubarak, Zenawi announced the beginning of construction of the most tremendous and massive dam in Africa, on the Blue Nile, with a total water storage capacity of 74 BCM. This capacity was a matter of wonder, because the total annual water flow of the Blue Nile does not exceed 48.85 BCM. This amount (74 BCM) of Blue Nile water would not be able to fill the two biggest Nile lakes, one in Ethiopia and the other in Egypt. Also, this amount would not be able to generate electric power of 6,000 megawatts (MW). This matter will be discussed later to explain the situation of Ethiopia in regard to Egypt, in which it appears that Ethiopia will start selling the water in the near future to the Gulf Arab States and then the era of financing water will begin, when water will be like oil. This one-sided decision to construct the dam is against and opposite to the step of the “Convention on the Law of the Non-navigational Uses of International Watercourses 1997” of the UN [21], which states that:

> Article 12: Notification concerning planned measures with possible adverse effects before a watercourse State implements or permits the implementation of planned measures which may have a significant adverse effect upon other watercourse states; it shall provide those States with timely notification thereof. Such notification shall be accompanied by available technical data and information, including the results of any environmental impact assessment, in order to enable the notified States to evaluate the possible effects of the planned measures.
>
> Article 13
> Period for reply to notification
> Unless otherwise agreed:
>
> (a) A watercourse State providing a notification under article 12 shall allow the notified States a period of six months within which to study and evaluate the possible effects of the planned measures and to communicate the findings to it;
> (b) This period shall, at the request of a notified State for which the evaluation of the planned measures poses particular difficulty, be extended for a period of six months..

Ethiopia did not follow these steps when it started building its vast and grand dam across the Blue Nile; it did not send the dam studies to Egypt or give Egypt 6 months, with the option of another 6 months to reply to its request. In addition, the Ethiopian government asked Egypt and Sudan to pay the cost of the environmental, hydrological, and socio-economic studies that Ethiopia should have done before starting the building of its dam.

5.6 Egypt Always Present in the Minds of Upstream Leaders (Water for Money)

In a study by the Ugandan researcher (James Mulira) published in 2010 with the famous editor Terji Tvedit (*The River Nile in the Post-colonial Age*) [31], the following statement was reported, on page 155:

> A parliamentary committee in Uganda concluded that new negotiation over the use of Nile waters would be the only way forward, and the state of East Africa, with tributaries towards Lake Victoria and Albert, must be receiving compensation for their water as well has sovereign decision over their use for agricultural irrigation and as sources of potable water for the population in these countries. Amon Muzoora, a member of the Uganda Parliament, specially proposed that: "Egypt should pay $1.2 million per annum to Uganda as a compensation for using Nile Water".

This statement is alarming and deserving answers of these questions:

1. Why should only Egypt pay Uganda, and not also Sudan and South Sudan?
2. Why should the payment be to Uganda only and not to all upstream countries?
3. Should Uganda, as a downstream country that does not share in the Nile water by any amount, or by a maximum of only 1.5% [3], also pay Burundi, Rwanda, Tanzania, and Kenya compensation for their river water delivered to Lake Victoria, and should Uganda also pay the DRC for the water of the Semiliki River that is delivered to Lake Albert?
4. Have we been talking about the natural resources of the River Nile and its catchment areas or are we talking about a special discovery or Ugandan invention? Has Egypt been digging the river runway from upstream to Egypt? Have Uganda and other upstream countries governed, and created the rain and clouds, or this is a natural phenomenon or a God-given destiny?

In another statement made by James Mulira [31], the following was written: "Charles Onyango Obbo declared: Egypt cannot enjoy the benefits of having access to the sea, while blocking landlocked countries like Uganda from profiting from the fact that it sits on the source of the Nile". G. Kateihwe reported; "God makes no mistakes; If Egypt wanted more water than any other countries through which the Nile flow, why didn't make another river from Mediterranean Sea to Egypt?! This means that all countries should be given a chance to use this water freely according to their needs".

This statement needs answering to the following questions:

1. What is the mistake made by Egypt to be blamed for its location and what is the advantage or mistake made by Uganda to be a landlocked country? Is it our choice or a result of our effort?

2. Why are the upstream countries always talking about Egypt only that should pay, without talking about Sudan or South Sudan?
3. What is the meaning of ‘use this water freely’? Does this mean that upstream countries can stop the water flow from their borders? Is this co-sharing a river or a private river? Does the country upstream own the river or is the river its natural resource?
4. Has the era of financing and trading water begun?

5.7 Absolute Territorial Sovereignty Versus Absolute Territorial Integrity

Yacob Arsano, the Ethiopian professor of history at Addis Ababa University, in his chapter on “Institutional Development and Water Management in the Ethiopian Nile Basin” (chapter 8 of the book, *The River Nile in the Post-colonial Age*, edited by Terje Tvedt; page 172) [36], explains how, in the following statement, the Ethiopian leader is thinking: “in the absence of defined and mutually agreed rules and procedures, riparian states may resort to involving principals they think most advantageous to their own respective national interests”. These principles include the doctrine of absolute territorial sovereignty and the doctrine of absolute territorial integrity. Actually the hydro-political discourse between Ethiopia and downstream nations revolves around the two doctrines. Hence it is surprising that downstream states reject the doctrine of absolute territorial sovereignty, while upstream states reject the doctrine of absolute territorial integrity”. He added: “Provisions that embody such nations as “reasonable” and provisions that embody the concepts of the “equitable sharing of water” and “international drainage basin” have been contested. The result has been less than universal support of the Helsinki Rules. Some states support the concept of “international watercourse”, others the concept of “international drainage basin”.

These ideas prompt the following responses:

1. This is the thinking of Ethiopia tricky and tricky, circumvent and circumvent, try to deceive every one about all principals.
2. The application of doctrine “absolute sovereignty” on the co-sharing natural resources such as river water is absolute hooligan and absolute savagery! Because this doctrine could be applied on the land inside the border of any country not for transient border resources or international rivers. This hooligan doctrine means any country can stop the transient of any river to their border without caring with life or death of the other neighborhoods people. This explain the completely absence of humanity thinking or the humanity believing, is just myself and everything after me should go to hill (Fig. 7).
3. As we explain Ethiopia believes only in sharing in international watercourse or just the water flow between the “Nile two banks” not in international drainage basin. Thus, Egypt should forget; and have no right to think about the huge rain

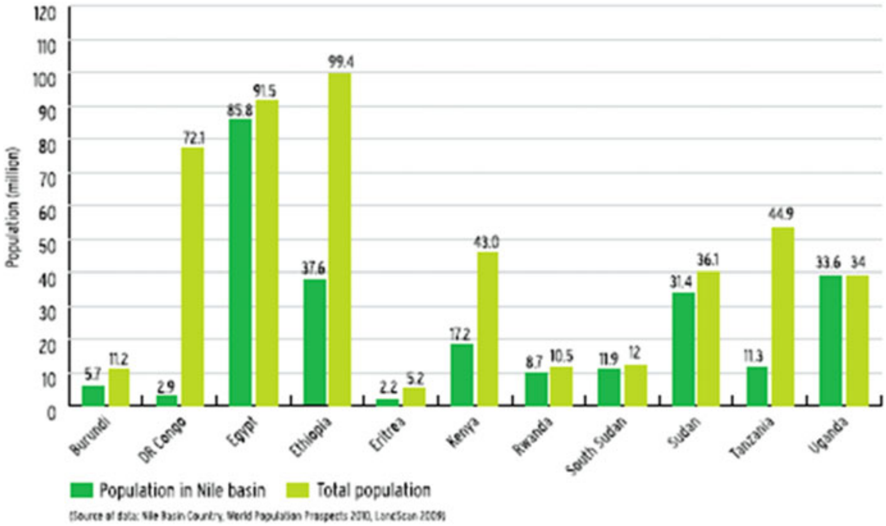
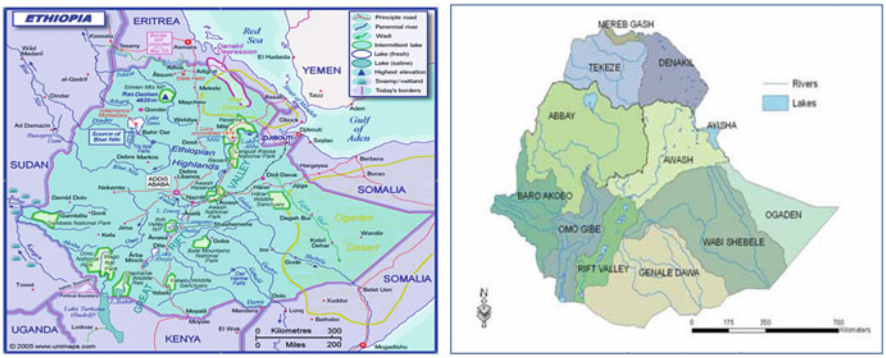


Fig. 7 Population living in the Nile Basin (2015) [18]



(a) (b)

Fig. 8 (**a**) Rivers in Ethiopia [18]. (**b**) The nine river basins in Ethiopia

water in Ethiopia, or the huge ground water in addition to the productivity of rainfed organic, pasture and livestock. Egypt have also no rights to talke about the other alternative "nine" basin rivers and even the population lives in the basin itself not in the all country lands, as seen in Fig. 8. The Egyptian population lives in the Nile basin is 94% against 37% in Ethiopia. The problem is Ethiopia looking for "equality" in water course of river and Egypt looking for "justice" by take the all water resources in each country.

4. Does that mean Ethiopia has no right in the Nile River water, or it should only watch the river during flowing from its land? Of course not, and it have the right to build any number of dams on the Nile and its tributaries but with no hazard to

the other riparian country. This will be achieved through make a new agreement with Egypt and Sudan to keep the water flow of blue Nile at their same discharge (effluent) before building the dams or with a minimum non-significant decrease to Egypt and Sudan, but Ethiopia never believe on any right of Egypt or Sudan in the Water of Nile river because they consider the Blue Nile and other rivers driven for Ethiopia; an private Ethiopian river!!. This is the Truth.

5. What the advantage of Ethiopia to be upstream country and what is the disadvantage of Egypt to be downstream country?

5.8 *Exaggeration and Overreaction*

Egypt suffers greatly from upstream countries' overreaction and exaggeration of their poverty rates, as these countries have always blamed Egypt for the high poverty rates in Ethiopia and other Nile Basin countries, even though the poverty rate in Egypt exceeded 33.5% in 2016; this is above the poverty rate in any upstream country. Also, Ethiopia always complains about the low rates of access to electricity for the Ethiopian people, but this too is an overreaction and exaggeration, as the next statement shows:

Eighty-three percent of Ethiopians currently lack access to electricity, with 94% still relying on fuel wood for daily cooking and heating [37]. Ethiopia possesses abundant water resources and hydropower potential, second only to the Democratic Republic of Congo in all of Africa, yet only 3% of this potential has been developed. Likewise, less than 5% of irrigable land in the Blue Nile basin has been developed for food production [38]. The Ethiopian government is therefore pursuing plans and

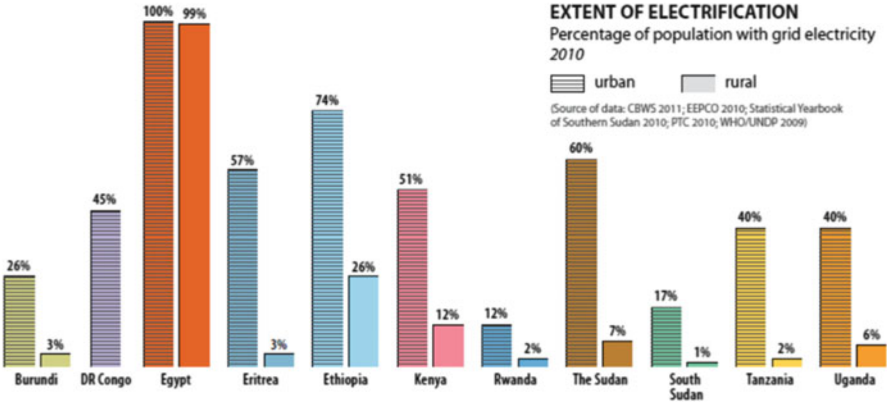


Fig. 9 Percentage of the population with access to electricity in Nile Basin countries [18]

programs to develop hydropower and irrigation to substantially reduce poverty and create an atmosphere for social change. It has been shown that access to electricity, including rural electrification, is a key to poverty reduction in Ethiopia [3, 4, 37–39].

The reply to this overreaction will be through the Nile Basin Initiative (NBI) report of 2016, as shown in Fig. 9.

The rate of the population's access to electricity in Ethiopia is not a maximum of 17%, as indicated above, but, according to a 2009 study, it was 74% in urban areas and 26% in rural areas [3]; also, according to NBI 2016 [18], access in 2012 was 100% in urban areas and 7.5% in rural areas.

6 The Story of the Blue Nile Dam

Everyone knows very well the value of the Blue Nile to Egypt, as the Blue Nile provides almost of 59–64% of the Nile water to the country. Thus, control of the Blue Nile means the control of every economic activity in Egypt. After the 1959 agreement between Egypt and Sudan, and the beginning of the construction of the Aswan High Dam by a Soviet construction company, Ethiopia Furred and that furred (Fury) also the British government, which was still the occupying colonial power in Kenya, Tanzania, and Uganda. In 1964, the United States Bureau for Reclamation (USBR) [40] performed an investigation and study of the hydrology of the upper Blue Nile Basin; this included making a plan for potential projects for dams for irrigation and hydroelectric power along the Blue Nile and Atbarah Rivers. The four major hydroelectric dams along the Blue Nile proposed by the United State Bureau of Reclamation (USBR) are presented in Tables 6, 7 and Figs. 10a, while the corrected sites are shown in Figs. 10b and 11.

The Karadobi Dam with its reservoir was planned to be located on the Guder River confluence, almost 385 km south of Lake Tana. The Mabil Dam would be 145 km downstream of the Karadobi Dam, 25 km downstream of the confluence with the Birr River. The Mendaia and Border Dams were suggested to be constructed about 175 km and 21 km upstream of the Sudan-Ethiopian border, respectively [40]. Further details and characteristics of the dams are provided in Tables 6 and 7. Figure 11 illustrates the height and head designs.

The total storage capacity of these four dams would be 73.1 BCM, which is equivalent to approximately 1.5 times the average annual runoff of the Blue Nile. The total expected generated power capacity would be 5,570 MW [41].

In 2002, Ethiopia proposed an Irrigation Development Plan to irrigate cropland along the western border region. The plan incorporates almost 250,000 ha, or 35% of the estimated total irrigable land in the Blue Nile Basin [38]. The source of irrigation is assumed to be from the Mendaia and Border reservoirs only. The Ethiopian irrigation plan includes approximately equal areas of small-scale and large-scale irrigation development, although no distinction between these two is made here.

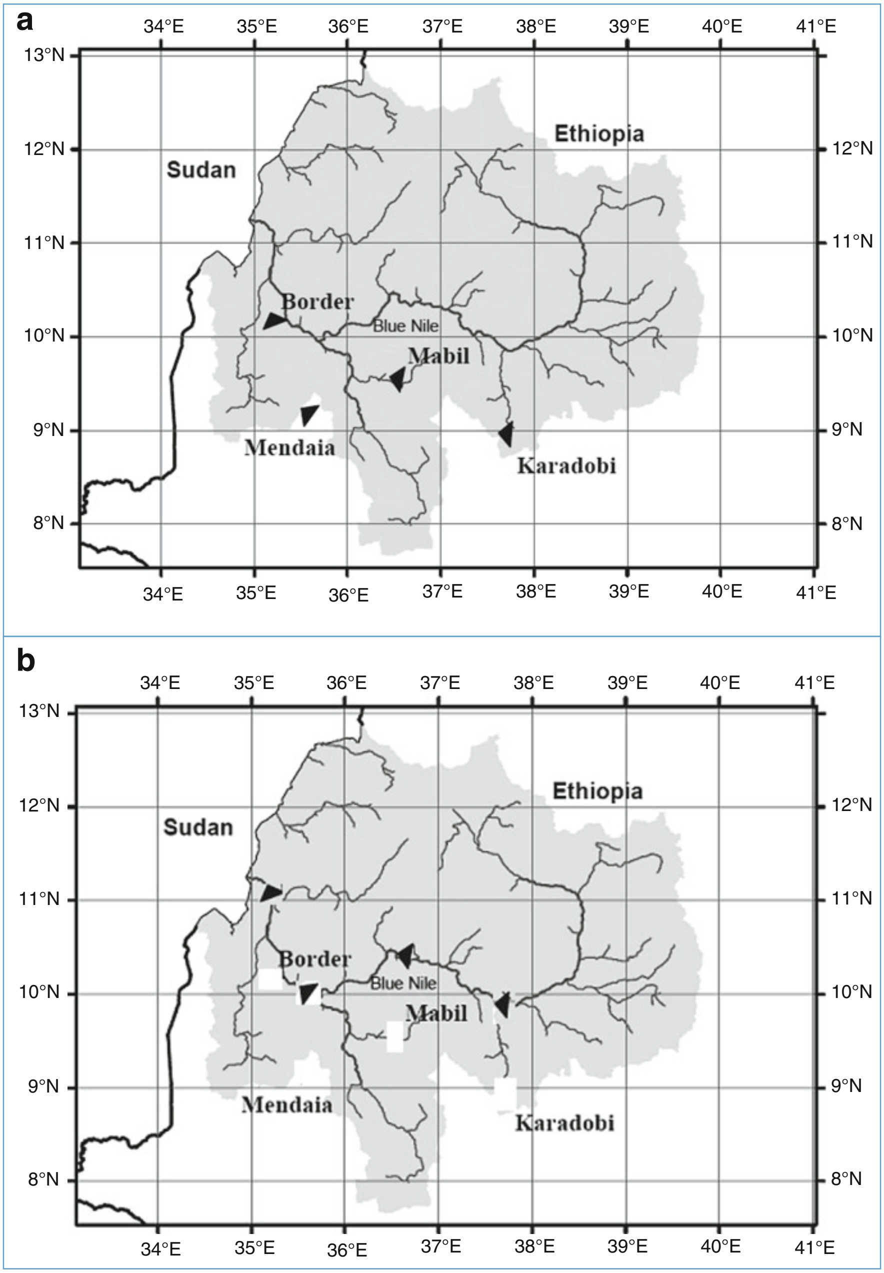


Fig. 10 (**a**, **b**) Proposed hydroelectric dams along the Blue Nile [40]

Table 6 Characteristics of proposed dams [40]

Project name	Structural height (m)	Crest length (m)	Design head	Minimum operational head (m)	Intake (m)
Karadobi	252	980	181.4	116	102.5
Mabil	171	856	113.6	73.8	59.7
Mendaia	164	1,134	117.4	109.8	70.4
Border	84.5	100	75	68.4	27.8

Table 7 Proposed reservoir and power characteristics [40]

Project name	Reservoir capacity (billion m^3)	Flow at design head (m^3/s)	Installed power at design head (MW)
Karadobi	32.5	948	1,350
Mabil	13.6	1,346	1,200
Mendaia	15.9	1,758	1,620
Border	11.1	2,378	1,400

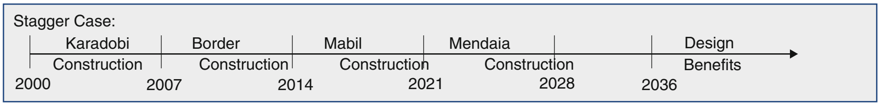


Fig. 11 General schematics of the Blue Nile dams staggered timeline [41]

(a) (b)

Fig. 12 Takeze Dam and the Sobat Basin [42, 43]

Thus, the Ethiopian leaders modified their plan to concrete the Border dam (the Grand Ethiopian Renaissance Dam; GERD) first, with the Karadobi dam given second priority.

Moreover, Ethiopia, during the past 10 years, has concentrated their thinking on surrounding (besieged or hedging) Egypt by threating its water resources from the Atbarah River (11–13%; 12 BCM and the Sobat River (12–13%; 12 BCM) in addition to the Blue Nile. They constructed the Takeze dam, with a water storage capacity of almost 10 BCM, and have made plans for another two dams on the Sobat River (Fig. 12), which means that every drop of water going to Egypt would be under the control of the Ethiopian government. The problem that is most worrying for Egypt is that all these dams were and will be constructed according to the sole and autonomous decisions made by Ethiopia, without any cooperation or negotiation with Egypt and Sudan, because Ethiopa believes only in the doctrine of absolute territorial sovereignty, as mentioned before (Fig. 12).

7 GERD Construction

1. *The reasons for Egyptian reservations*
   Ethiopia insisted on imposing an advance condition and a contract with an international panel of experts (IPoE) to evaluate Ethiopian studies of GERD. Legally, this process should be performed before beginning the work on construction of a dam. Ethiopia considers that the GERD is a dam under construction and not a project under study or under consultation, even though nothing had yet been performed. In addition, no environmental or hydrological and socio-economic study was established, although in 2011 a cornerstone had been laid. Thus, Ethiopia imposed and predetermined a policy of power or exploited the bad circumstances of their neighbor after the neighbor's president was replaced.
2. *Is this dam for generating power only or for storing water?*

   Ethiopia claims that the GERD is a dam that will only be used generate electricity. During the writing of the GERD declaration document, which was signed in Khartoum on 23 March 2015 ('Declaration of Principles', signed by Egypt, Sudan, and Ethiopia) [44], Ethiopia described the purpose of the dam as being to "generate power and contribute to economic development" and refused to say "to generate power only", as termed in principle two, as follows:

   Principles of development, regional integration, and sustainability

   "The purpose of the Renaissance Dam is to generate power, contribute to economic development, promote cooperation beyond borders, and [promote] regional integration through generating clean sustainable energy that can be relied on" [44].

   Surely, economic development includes industrial and agricultural activity, especially if there is arable land surrounding the dam lake, and such development might also include the storage of water for sailing, meaning that there are multiple proposals for this dam. This explains why Egypt sees an absence of transparency by Ethiopia.

The second point of concern for Egypt is the very low electricity generation efficiency of the GEDR compared with other dams both in and outside Ethiopia. This coefficient will not exceed 33% [45, 46], which makes Egypt believe that this dam was constructed for a purpose other than generating electricity. This is because another dam, or alternatively, the construction two small dams, may generate more electricity than this oversized dam. Thus, Egypt advised Ethiopia of this alternative solution, but Ethiopia refused to consider it (my experience through sharing many official and unofficial events and studies by the Egyptian government).

What does lower efficiency mean?

With efficiency as low as 33%, the electricity that will be produced from the GERD is equivalent to a power plant with an installed capacity of 2,872 MW that has an efficiency of 60%. The total cost of the GERD could be reduced by at least 40–45% by building a smaller dam with higher efficiency [45, 46].

Seasonal and annual variations in stream flow have a significant impact on hydropower plants. Climate change will make the stream flow even more variable in the future (Fig. 13).

3. The excessive Ethiopian campaign about the benefits of the GERD depends on incorrect information. Technical articles by the Ethiopian-American professor of mechanical engineering and Director of the Center for Renewable Energy and Energy Efficiency at San Diego State University (Asfaw Beyene) were published in 2013 [45, 47], in which he stated that the dam is 300% oversized–the load factor for a dam designed to produce 6,000 MW would be only about 30%. If it were "right-sized" to 2,000 MW, its load factor would be about 90%. The GERD face several criticize unless the dam's sizing is corrected. Moreover, the harmful effect of the GERD was stated by NBI 2012 [3] through a study of the effects of climate variation and climate change that will increase with hydropower dams.

Climate variability and change

Large areas of the Nile Basin are vulnerable to drought because of high variability in rainfall and high evapotranspiration rates. Seasonal water shortages

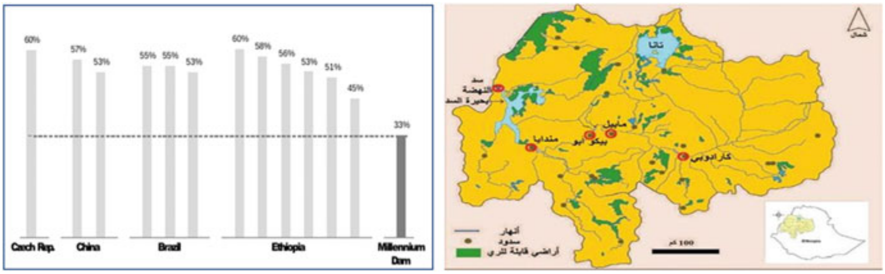


Fig. 13 Electricity generation coefficient of the Grand Ethiopian Renaissance Dam (GERD) and the arable land around the GERD lake [45, 46]

associated with natural climate variability make it difficult to maintain peak generation capacity throughout the year, and may reduce the long-term economic feasibility of candidate hydropower projects. The negative impacts of climate on the power sector are expected to increase significantly with global climate change.

4. During the negotiations between Egypt and Ethiopia, the standpoint of Egypt is that Ethiopia should ultimately omit building a saddle dam to decrease the water storage capacity to 13 BCM, or reduce its height to only 20 m to lower the water storage capacity to 25–30 BCM. This will raise the efficiency of generating electricity to more than 65%. This may also end the dispute or avert future conflict with Egypt when the impact of this substantial oversized dam touches everyone in Egypt. Egypt is almost all desert and the population of 104 million according the last population survey in 2017 lives in only 7% of its total area; the remainder of the country suffers from dominant drought and dryness. About 97% of the Egyptian population lives in the Nile Basin adjacent to the river banks. However, Ethiopia alleges that Egypt cultivates rice although it is a desert country. Does Egypt cultivate rice in the desert? Egypt does cultivate rice, but only in the heavy clay soils of the north Nile Delta land, not exceeding an area of 1–1.5 million acre (0.42–0.63 ha), to control the build-up of salinity that threatens the Delta. The soils in the North delta were 47% saline, owing to the incursion of Mediterranean Sea water . Rice cultivation was the only way to leach out the salt accumulation and prevent land degradation after preventing flooding by the High Dam (1970). Ethiopia also claims that Egypt has stolen Ethiopian water. Where does that stolen water go as Egypt is surrounded by desert? Is Egypt greening the desert and living on 25% of its area instead of just 7% (see Fig. 14)? The agriculture sector in Egypt, the sector of poor people, consumes 103% of the

Fig. 14 Map of Egypt. Google satellite

Nile water share and 85% of all the water resources, yet Ethiopia claims that Egypt sells water to wealthy people to make lagoons and swimming pools. Finally, these factors reflect how Ethiopia believes that they own the Nile and should watch the uses of its water in other countries.

5. As the former Ethiopian Prime Minister Meles Zenawi once protested: "While Egypt is taking the Nile water to transform the Sahara Desert into something green, we in Ethiopia – who are the source of 85% of that water – are denied the possibility of using it to feed ourselves." (Several readings in the Egyptian and international press).

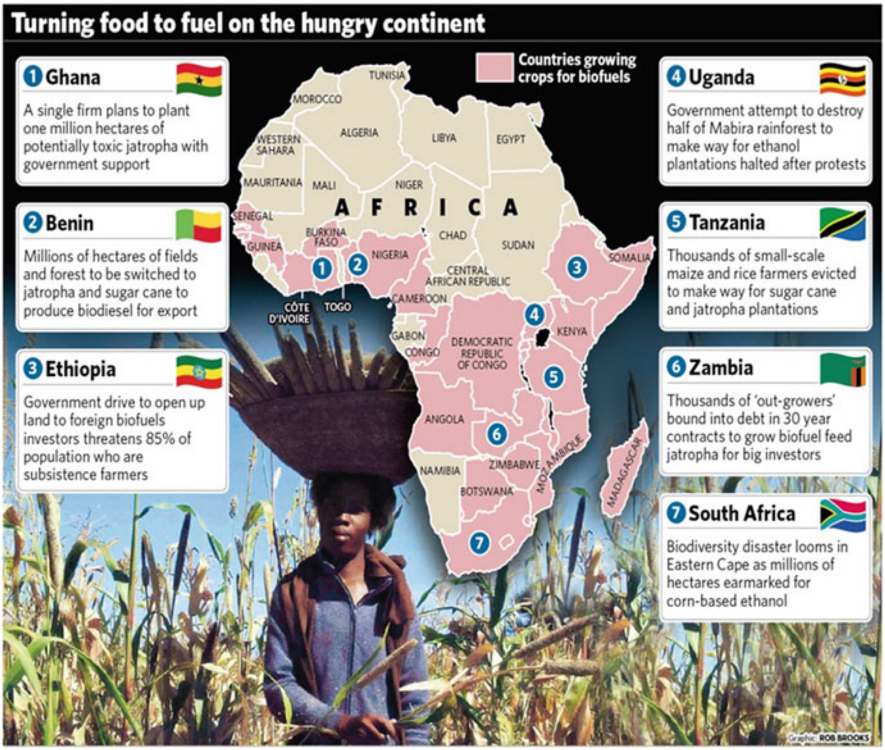
   Are you feeding your people, Mr. Prime Minister, with biofuel that Ethiopia planted instead of foods, as the UN mentioned "turning food to fuel on the hungry continent"? The total area already allocated to 87 biofuel companies from 25 countries reached 3,791,602 ha in 2015 [48]. Also, almost 10 million ha are under cultivation with grain and double this area is already cultivated with economic crops such as cottonseed oil, a cop that exceeds 10.5 million ha (https://tradingeconomics.com/ethiopia/arable-land-percent-of-land-area-wb-data.html). Also, such crops as sugarcane, sorghum, organic foods for export, and cut flowers are also cultivated. In contrast, the entire area under cultivation in Egypt does not exceed 3.5 ha, or one-third of the Ethiopian lands that are already under cultivation with biofuel or commercial crops. Egypt is the only country in the Nile Basin that needs to save food for their people; there is a profound food shortage, with more than 60% of its food needing to be imported. Egypt imports 70% of its needed wheat (first in the top list of food-importing countries), 70% of its maize (fourth in the top list of food-importing countries), 97% of its edible oil (seventh in the top list of food-importing countries). Moreover, Egypt imports 100% of its requirements for lentils, 80% of its needed faba beans, 35% of its needed sugar, 60% of its needed red meat, 10% of its needed poultry, and 60% of its needed butter and butter oil [4]. Does Ethiopia have the same list of imported food? Or does Ethiopia cultivate crops for export purposes or export electricity? The truth is that Egypt has the least amount of arable land of the main Nile Basin countries. For example, Sudan has 84 million ha, Ethiopia 35.3 million ha, Tanzania 51.3 million ha, Uganda 14.7 million ha, and Kenya 33.6 million ha [49–52]. The total area of Egypt is fourfold that of Uganda and twofold that of Kenya and almost the same as that of Tanzania and that of Ethiopia.

   The Ethiopian researcher Asnake Demena [48] has stated the following about the tragic truth of land grabbing for biofuels in Ethiopia:

   "More than 87 biofuel companies from 25 different countries are operating on 3,791,602 hectares of land between 2005 and 2012 [in] almost in all regional states in Ethiopia except that of Tigray. This makes Ethiopia the only country in the world in which large-scale land is considered as a development strategy." [48]. Figure 15 shows the poor African countries that are producing biofuel instead of food (Table 8).

6. *Critical Note That Makes Sense*

   Entebbe Agreement define the principle of not causing significant damage as: "in case significant damage is caused to one of these countries, the country causing the damage, in the absence of an agreement over that [damaging] action,



Turning food to fuel on the hungry continent

Countries growing crops for biofuels

① Ghana

A single firm plans to plant one million hectares of potentially toxic jatropha with government support

② Benin

Millions of hectares of fields and forest to be switched to jatropha and sugar cane to produce biodiesel for export

③ Ethiopia

Government drive to open up land to foreign biofuels investors threatens 85% of population who are subsistence farmers

④ Uganda

Government attempt to destroy half of Mabira rainforest to make way for ethanol plantations halted after protests

⑤ Tanzania

Thousands of small-scale maize and rice farmers evicted to make way for sugar cane and jatropha plantations

⑥ Zambia

Thousands of 'out-growers' bound into debt in 30 year contracts to grow biofuel feed jatropha for big investors

⑦ South Africa

Biodiversity disaster looms in Eastern Cape as millions of hectares earmarked for corn-based ethanol

Fig. 15 Turning food to fuel in the hungry continent [53]

Table 8 Comparison of agricultural land and land use in Egypt and Ethiopia in 2007 [53]

Country	Agriculture area (1,000 ha)	Agriculture area per capita (ha)	Arable land (1,000 ha)	Permanent crop (1,000 ha)	Cereal harvested area (1,000 ha)
Egypt	3.538	0.0	3.018	520	2,850
Ethiopia	35.077	0.4	14.038	1,039	10,511

[is to take] all the necessary procedures to alleviate this damage, and discuss compensation whenever convenient" [44]. However, it seems that 'Whenever convenient' means 'will never pay compensation'.

Cost and benefits: Ethiopia does not care about the costs and benefits for all Nile Basin countries, as mentioned by the NBI 2012. "*Cost and benefit sharing* – In a transboundary basin with no legal/institutional framework for cooperative development of basin resources there is usually no mechanism for quantifying and equitably sharing the costs and benefits related to investment projects, making it difficult to proceed with such projects" [3].

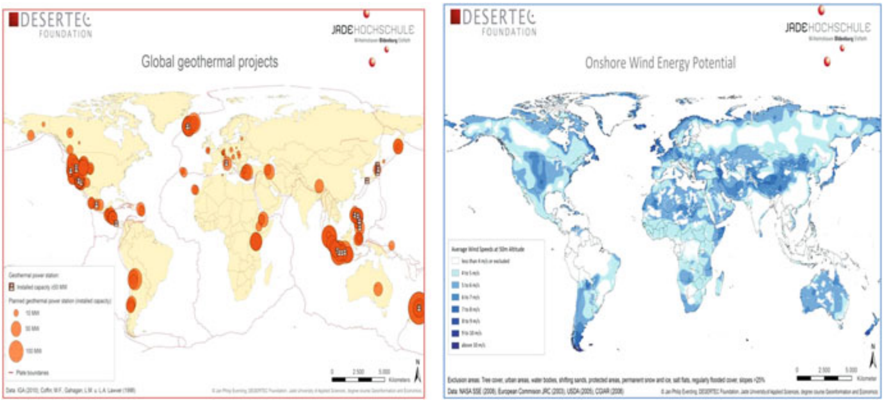


Fig. 16 Geothermal and wind energy potential maps including Ethiopia [54]

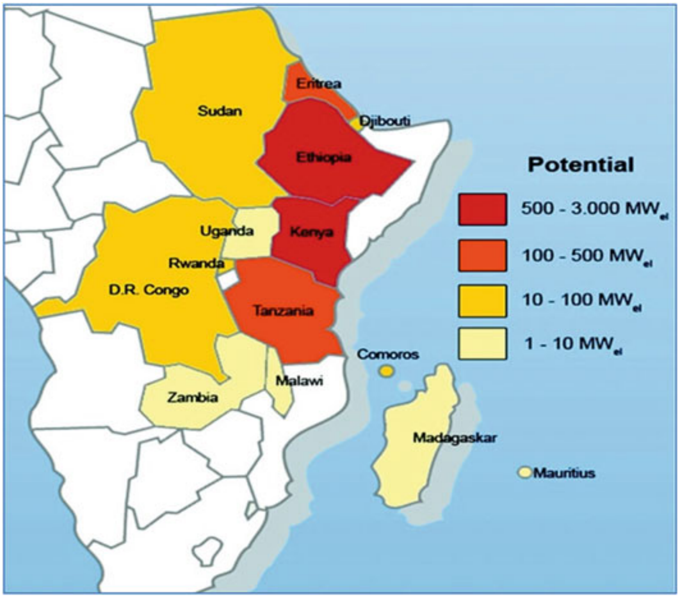


Fig. 17 Geothermal potential in east Africa [55]

Renewable power options: In the short-term, the region needs to promote the implementation of clean renewable power options, such as geothermal, wind, and solar, which are environmentally friendly and have much shorter incubation periods than hydropower. The low risk and short implementation period renders renewable power options very attractive for private investment if the tariff is right (Figs. 16 and 17).

Ethiopia has another two potential sources of power; the first, geothermal, which may produce up to 3,000 MW, and the second, wind power, which may produce up to 12,000 MW. It would therefore be better for Ethiopia to delay a conflict with Egypt by giving priority to geothermal and wind power. This could be better than exploiting the circumstances in Egypt after the revolution of January 2011 to construct a dam with no environmental, hydrological, or socio-economic studies, as required by the May 2013 report of the IPoE [56].

Lesson learned from the Ethiopia-Kenya experiment: Ethiopia asked its southern neighbor, Kenya, to approve the construction of the Gilgel Gibe III Dam in Ethiopia on the Omo River, which connects the two countries, and guaranteed to not decrease even a cup of Kenya's water share. What we followed about that and as Kenyan call and urges the world to save Turkana (https://www.internationalrivers.org/blogs/266-0); (http://www.unocha.org/story/kenya-%E2%80%9Ccoordination-can-save-our-lives%E2%80%9D-says-turkana-village-elder); Ethiopia constructed a series of Gibe dams, with three dams being constructed in 2017, and a plan to build another two dams, a proposed total of five. Lake Turkana, into which the Omo River flows, is classified as one of the most attractive desert lakes for tourists [2], but it has become a salty lake and more than 200,000 Kenyans have migrated south.

8 Conclusion and Recommendations

Historically and currently, Egypt has never refused to allow the construction of dams in the upstream Nile countries. Egypt even funded the first dam in Uganda, on the mouth of Lake Victoria – the Owen Falls Dam (now named the Nalubaale Power Station). Egypt also approved the Kiira dams behind the Owen Falls Dam. Moreover, Egypt accepted the Takeze dam in Ethiopia, which was finished in 2009, because its storage capacity was only 9 BCM. Nonetheless, Egypt has the right to refuse the mega dams in upstream Nile countries, just as the UN Water law regulates. That is why Egypt refuses to accept the GERD, which has a total storage capacity of 74 BCM, in addition to an expected water loss caused by scattered sprays of the turbines, evaporation from the huge storage areas (500 km^2), and deep seepage (percolation) from the bottom of the dam lakes. This dam's storage capacity exceeds by almost twofold the total average water discharge of small rivers such as the Blue Nile, which has a total discharge of only 49 BCM/year. This small river will never be able to fill two large lakes at the same time; one in Ethiopia with a capacity of almost 90 BCM and the second in Egypt in front of the Aswan High Dam with another 90 BCM of live capacity from its total capacity of 162 BCM .

Despite the dispute between downstream and upstream countries, the countries should look for a framework for collective work to tame the water loss in the Nile Basin swamps and wetlands. Only 4% of the catchment water and precipitation in the upstream reaches the Nile stream, while more than 1,600 BCM runs outside the Nile River course. Water harvesting and the taming of swamp water may add more than 100 BCM of water to the Nile stream, an amount which could solve most of the existing water requirement problems between Ethiopia, Sudan, and Egypt. Egypt has always received demands from the upstream countries to pay for water, which reflects the deep beliefs of these countries that they own the Nile River. Nile Basin countries have the capability to achieve food security for all their people and perhaps for the entire African population, by efficiently using the plenty of the fertile lands and the available water. The GERD could be welcome if Ethiopia omits the saddle dam or lowers its height to 20–30 m instead of 50 m, which may reduce the storage capacity to 25–30 BCM instead of 74 BCM.

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The Grand Ethiopian Renaissance Dam and the Ethiopian Challenge of Hydropolitical Hegemony on the Nile Basin

Mohamed Salman Tayie

Contents

Abstract It is clear that recent developments in the Grand Ethiopian Renaissance Dam (GERD) file are witnessing an escalation of the conflict in hydropolitical interactions between the Egyptian and Ethiopian sides.

Although "the Renaissance Dam" – known previously as "Border Dam" – was one of the dams and water projects proposed by the United States Bureau of Reclamation (USBR) in its 1964 report on the exploitation of the waters of the Blue Nile, yet the new version of the Border Dam as reflected in the GERD version is considered as a stimulus for an Egyptian-Ethiopian conflict. This comes true especially in the light of Ethiopia's quest for imposing a fait accompli, the deliberate consumption of time in negotiations, and the non-making of concessions in addition to the unilateral moves.

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Constructing GERD, Ethiopia aims to achieve some developmental declared goals in addition to some undeclared political and strategic objectives. Among these objectives is the imposing of “hydroelectric hegemony” on the Nile Basin which would consequently lead to achieving political and geostrategic leadership in that Basin. In its turn, this would lead to sieging of Egypt politically and strategically in the vicinity of its African circle/region.

The study aims at verifying the following major hypothesis: The more the Ethiopian intransigence and obstinacy and its insistence on the construction of GERD in accordance with the declared technical specifications, the increased risks, damage and negative effects on Egyptian national security. Furthermore, Ethiopia would be able to achieve hydroelectric hegemony on the Nile Basin.

Does Ethiopia aim to build GERD to achieve hydropolitical domination as well as development goals? What is the evidence?

Keywords Border Dam, Grand Ethiopian Renaissance Dam (GERD), “Harmon” principle, Hydro-hegemony, Hydropolitical hegemony, International river, Millennium Dam, No-harm principle, Prior notification condition, Transboundary river, Water security

1 Introduction

The first decade of the new millennium witnessed long-term negotiations – the Nile Basin Cooperative Framework Agreement – between downstream and upstream Nile Basin countries and which lasted for about 5 years (2006–2010). However, these negotiations ended in failure as six Nile Basin countries unilaterally signed the Framework Agreement on Entebbe to establish the Nile Basin Commission in 2010 while excluding Egypt and the Sudan.

The most complex and important development in the Nile Basin occurred when Ethiopia exploited Egypt’s internal confusion during the January 25, 2011, revolution and unilaterally announced in February 2011 its project “Grand Ethiopian Renaissance Dam” (GERD) according to technical specifications that threaten the Egyptian water security. On April 2, 2011, Ethiopia laid the foundation stone for GERD, thus starting a new episode of water conflict in the Nile Basin.

In turn, the negative developments in the GERD file have contributed to the escalation of the conflict in the Egyptian-Ethiopian relations. As a sign of such escalation, Egypt announced in November 2017 the failure and stall of the ongoing negotiations concerning GERD. This announcement was the second after having declared a first failure in February 2014. The crisis of the GERD between Egypt and Ethiopia escalated following the announcement by the official spokesman of the Ministry of Irrigation of Egypt’s readiness for international arbitration with Ethiopia on GERD.

In reaction to these developments, the Egyptian President Abdel Fattah el-Sisi said:

> No one can approach the waters of Egypt ... The waters of Egypt are a matter of life or death for our people.

It is clear that the words of "el-Sisi" bear an indication of opening all options to the Egyptian authorities to respond to the Ethiopian intransigence in the GERD negotiations.

However, the situation became more tense due to the Sudanese-Ethiopian rapprochement in views and attitudes concerning GERD. This rapprochement has led to more strain in the Egyptian-Sudanese relations recently especially after Egypt's request for mediation and its selection of the World Bank as a mediator on GERD without coordination with the Sudan.

This crisis has raised great concerns among large sectors of the Egyptian society, especially in light of recalling such statements as "water war," "water militarization," "military management of the GERD crisis," "water terrorism," and "Ethiopian hydro-hegemony over the Nile Basin" [1, 2].

The current developments of the GERD file have imposed an urgent necessity for analyzing the hydropolitical scene in the Nile Basin and the political and legal problems that arise from Ethiopia's non-compliance with the "no-harm" or "prior notification" principles before implementing this huge project. It became clear that Ethiopia's main aim of the construction of GERD on the Blue Nile is primarily a political-strategic one; the aim is to achieve "hydropolitical hegemony" on the Nile Basin.

2 The Hydro-Hegemony Concept

The concept of "hegemony" emerged in the literature of international relations during the Cold War. Volgy defines hegemony as "the position of possessing power and the ability to change the rules and customs of existing international systems" [3]. On the other hand, Gadzey defines it as "the ability of the dominant state to control the rest of the countries according to its will, with particular focus on its competitors" [4].

The concept of hegemony has various forms. These include political, economic, and cultural hegemony. However, with the new millennium, the concept of hegemony shifted to the field of water studies and hence emerged the concept of hydro-hegemony. The literature reveals how the concept of "hydro-hegemony" has developed over the past decade and how it has contributed to the understanding and interpretation of many water policies around the world. This comes through the understanding of the dynamics of power that control international waters in addition to the understanding and explaining of how powerful riparian countries use some implicit means to maintain their control and also to control the rules of the game.

Hydro-hegemony is "the active hegemony of the international river basin and it occurs when international water flows are controlled by the stronger state. This hegemony can be achieved through strategies of control over water resources"

[5]. Hydro-hegemony determines the nature of the river-like relationship that exists among several countries brought together by the interactions of conflict and cooperation with the river's dominant, which has greater control over the river's waters" [6].

Hydro-hegemony is most pronounced in the reduction of power of the dominant of water affairs through a variety of material and normative means. This hegemony is achieved through a combination of tactics such as pressure and intimidation, treaties, knowledge building, and so forth [7]. Notably, hydro-hegemony is exercised by the dominant party in the river basin through ideas, beliefs, knowledge, institutions, agreements, and so forth [8].

Hydro-hegemony can also be achieved through the success of a State in the international river basin in imposing its ideological vision in order to preserve its interests. This indicates the success of the dominant State in presenting its vision and ideology to the other forces in the basin as well as its ability to prevent any changes that hinder the status of hegemony [9].

Some studies have analyzed how political power is distributed asymmetrically within international river basins, where a river State maintains a dominant position within the basin and often receives more than a fair share of the available water resources. It is notable that the basin dominant tends to adopt a political discourse that focuses on concepts such as "sovereignty," "benefit-sharing," and "water justice" in proportion to its interests [10].

The "hydro-hegemony framework" helps to understand "who gets the quantity of water, how and why" – according to H. Lasswell's definition of policy – rather than assuming reciprocal duality of conflict and cooperation leading to absolute control over water or joint water management on an equal footing. Consequently, power is seen in the context of hydro-hegemony as "the main determinant of successful implementation of controlling water resources."

Although "hydro-hegemony" can be interpreted within the framework of the realist school of international relations, yet international relations theories require development to deal with international water issues. This development is specifically required to understand and interpret international interactions – whether based on struggle or cooperation – that are related to hydro-hegemony in a way that avoids the current discourse about "water wars" and "water peace" [11].

Hydro-hegemony can either involve "enlightened leadership" or "repressive hegemony." Hegemony can provide order and stability to ensure water flow to the major states, and on the other side, the hegemony may be accompanied by exorbitant costs for the weaker states in the political equation, resulting in the lack of control on the organization and management of the river decisions and absence of appropriate allocation of water for those states. This may cause political unrest, opening the door for severe water conflicts [12]. The negative type of the hydropolitical hegemony refers to "the conflict of departments, political and geo-strategic interests between upstream and downstream states, where the upstream states use the water to get more power, while the downstream states use power to get more water" [13].

It is noticeable that the negative hydro-hegemony is the most prevalent in the Middle East river basins. The empirical cases in the Middle East river basins – the

Nile, Jordan, Tigris, and Euphrates – show that hydro-hegemony, even though not conducive to wars, has led to low and moderate conflicts [7].

2.1 *Indicators of Hydro-Hegemony*

Hydro-hegemony occurs when a state within an international river basin confirms its power over other riparian states, including the upstream states. This is achieved through three indicators [14–16]:

1. Location of the river State: upstream or downstream. The location of the river State gives it an advantage provided by the geography for the upstream State to manipulate the river's water flows as well as giving it the ability to prevent or divert them.
2. Relative power of the State: such power consists of the following three power dimensions [17, 18]:
   (a) Material power: It includes the ability of the State to mobilize and transform its capabilities into a force, such as economic power, military power, technological prowess, and international political power [19].
   (b) Ability to bargain: which means the negotiating power of the State. This includes the ability to persuade other parties to make concessions and the ability to reach compromises.
   (c) Ideational power: which means the ability of the river State to impose certain ideas and visions. In short, ideological power allows the basin dominant to dominate political ideas and perceptions in neighboring riparian countries.
3. Exploitation potential of water resources in the basin through the ability to build water infrastructure, as well as the storage capacity of the river State (Figs. 1 and 2).

2.2 *Hydro-Hegemony and International Law*

The concept of hydro-hegemony provides a framework for interpreting the relationship between the use of force and water sharing, regardless of the rules of the international law, since the framework of hydro-hegemony shows the hidden use of force used by the State to perpetuate inequitable arrangements for water sharing. Thus, international water law must include in its principles these hidden practices of hegemony. For the "carrot" of international law to be attractive, the "stick" of domination must be removed first, because hydro-hegemony reduces the effectiveness of international legal principles [20].

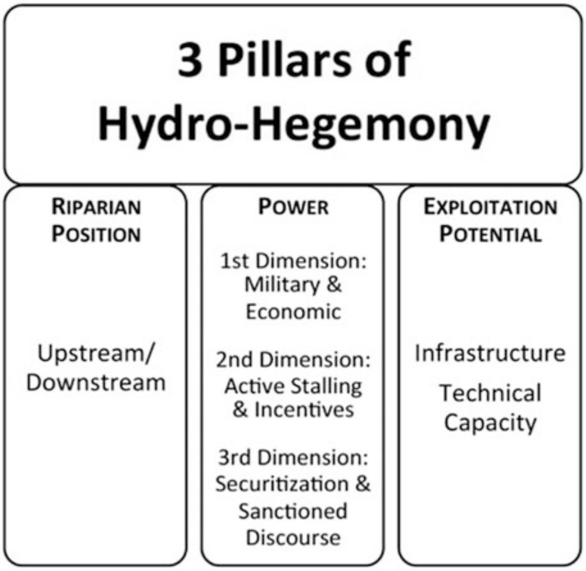

Fig. 1 The original pillars of hydro-hegemony [7]

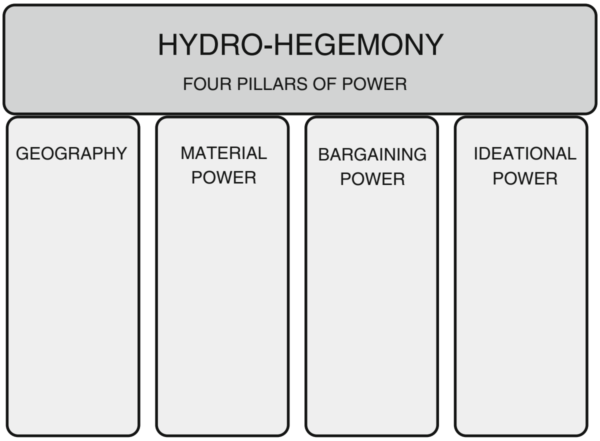

Fig. 2 The revised pillars of hydro-hegemony [5]

The analysis of hydro-hegemony from the perspective of international water law shows that international water laws are an element of power relations between river states as they are considered as a source of structural and negotiating power. Hence, international water law principles tend to increase the legitimacy of downstream countries in negotiations [21]. Since green water and virtual water are also subject to hydro-hegemony – like blue water – international law can be a useful tool in addressing inequalities arising from hydro-hegemony, which, in turn, limits the scope of international law currently [22].

3 The Strategic Importance of the Nile Water in Egypt

The Nile River occupies a pivotal position in the life of Egypt and the Egyptians. On its shores, one of the most ancient human civilizations was long established. The Nile has always been a witness on the developments of politics, economy, and society that the Egyptian State has experienced in different times and ages. In fact, no river had the same role played by the Nile in the life of Egypt. The Nile did not only create Egypt's water and agricultural system but also its political and economic system in addition to its religious faith and its national unity. In order to unify the water system and coordinate irrigation schedules in the provinces, there emerged the political unity, the centralized State, and hence national unity was consolidated.

Perhaps the greatest expression of this fact is the embodiment of the Egyptian monuments of an exquisite depiction of a composite image of the pharaoh united with the symbol of the Nile "Hapi" and the symbol of justice "Maat." Thus, the three "the pharaoh, Hapi, and Maat" formed the unity of the political system and the rules of distributing water resources in accordance with justice and equality. The love of the Nile deepened in the hearts of the Egyptians to the extent that it became a tool for oath. Moreover, preserving and maintaining the Nile against pollution became an oath when taking up major positions in the State of ancient Egyptian civilization [23].

Being the main source of fresh water, the Nile consequently becomes most important for the Egyptians. Furthermore, Egypt relies on the Nile water almost entirely for its agricultural, industrial, and domestic uses. It provides about 96.5% of Egypt's annual water needs, while other sources such as rain, underground water, and desalination of agricultural and sanitary drainage water provide no more than 3.5–5% at best. Therefore, any shortage of water coming to Egypt from the Nile River has a negative and direct impact on its agricultural and industrial production. Therefore, Egypt's share of the Nile water is considered as the minimum required to meet the water needs, unlike all other Nile Basin countries which have heavy rain, large quantities of underground water, and many other rivers. It is no doubt, then, that the Nile has always been the origin of life in Egypt, which was and still remains the gift of the Nile [24, 25].

It is a fact that the Nile River is the longest river in Africa and the world. Its length extends to a distance of 6,695 km, according to the British Encyclopedia, measured from its highest point on the plateau of the tropical lakes (at the farthest point on The Ruvyironza (or Luvironza) River, a branch of The Rurubu River in Burundi) to the last point in its estuary in the Mediterranean Sea. In addition, the Nile River is the longest in the African continent and also has the largest number of riparian states [26, 27]. Yet despite all these facts, the Nile River has a low water flow of no more than 84 billion cubic meter (BCM) per year and, thus, is classified as one of the least-flowing rivers in the world [28–30] (see Fig. 3).

The various studies of the sources of Nile River revenues indicate that it receives its water revenues from two sources: the plateau of the tropical lakes and the Ethiopian plateau. With regard to the plateau of the tropical lakes, it starts from

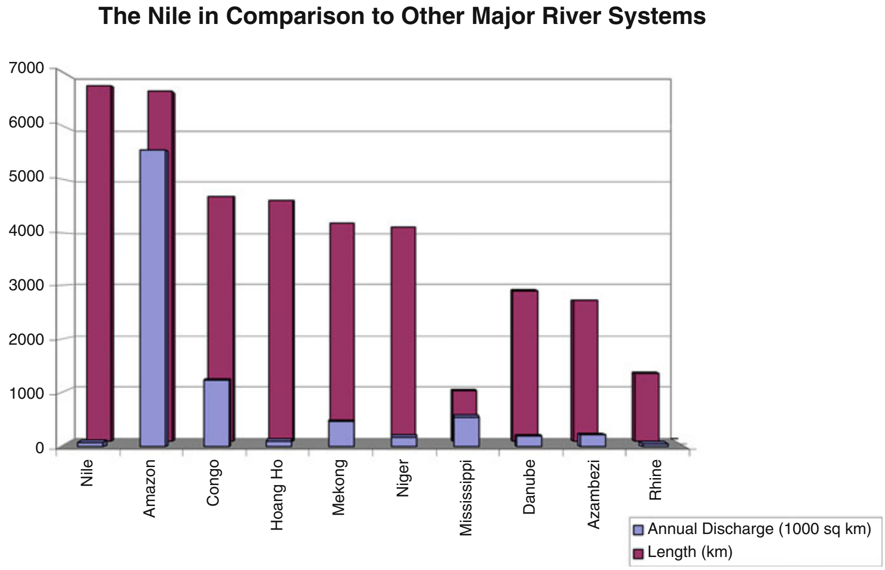

Fig. 3 Nile River length and discharge compared to some other rivers in the world [26, 28, 29]

Lake Victoria as the largest freshwater lake in the world with an area of about 69,000 km^2. Its annual volume of water is estimated about 118 BCM, of which only 23.5 BCM are spent in “Victoria” Nile. This Nile is the only way out for the water of the lake through a number of waterfalls called “Ribon” and Owen Falls. The tropical lakes contribute only about 13 BCM, which is about 15% of the Nile River revenues.

The second stream of Nile, which is the most important, is the Ethiopian plateau, which rises about 1,800 m from the sea. This second stream provides about 71 BCM of water at the main Nile in Aswan; this amount of water constitutes about 85% of the Nile revenues which come through three main rivers: the Blue Nile (Abay); the Blue Nile revenue in Khartoum when it meets the White Nile in the area of Al-Mekren amounts to about 54 BCM, of which about 48 BCM reaches Aswan. Thus, it constitutes about 60% of the Nile River. The second river is Subat River (Baro-Akobo) which contributes about 11 BCM, while the third river is the Atbara River (Tekeze) which contributes about 11 BCM [31–37].

The importance of the Blue Nile and the Ethiopian Plateau, which provides about 86% of the revenue (compared to only 14% of the tropical lake plateau), is thus recognized being the largest donor of water to the Egyptian Nile. Gamal Hamdan was right when he said: “If Egypt is the gift of the Nile, and if the Nile is the gift of the flood, then Egypt is the gift of the flood of the Blue Nile” [38].

It is no doubt that Egypt’s relationship with the Nile clearly reflects the characteristics of this river, which is almost unique to other international rivers. This river has taken full control – almost till today – of the economy and life of the Egyptian State. In addition, the first beneficiary State of this river – Egypt – has none of its sources on its territory, which always forced her to have a special relationship with those countries which have such sources within their territories and on which the river passes long distances before entering the Egyptian border. In light of the above, the exceptional importance of the Nile Basin countries in general and Ethiopia in particular can be explained in Egyptian foreign policy [39].

In fact, this general outline of the importance of Nile water for Egypt can be elaborated – a little – as follows [40, 41]:

- The Nile River is considered the first – if not the only – source of the valley water in Egypt, ancient and modern, and that there is no other source of water comparable to it.
- Egypt is the only country in the Nile Basin that consumes almost all its annual water revenues. The following table shows the degree of dependence of the Nile Basin countries on its water (Table 1).

It can be said that Egypt has inevitable interests in the Nile water. These interests are of such importance that they are almost incomparable to any other countries' interests in the Nile Basin. Therefore, it is not surprising that Egypt has always turned its attention – since the beginning of its known history – to the south where the sources of the Nile and its tributaries are located. This was for one main goal which is preventing these sources from falling into the hands of hostile forces or establishing projects that would affect the natural water flow to Egypt [42, 43].

In our estimation, this conclusion holds true to the past as it is to the present, and to the prospects for the future, it has more emphasis.

4 The Ethiopian Dream of Hegemony on the Nile Historically

The reading of historical precedents reveals that the Ethiopian emperors promoted the notion of "Ethiopian domination over the sources of the Nile as well as their ability to turn the course of the Blue Nile at any time as a means of political and

Table 1 The degree of dependence of Nile Basin countries on river water [40, 41]

Ratio of dependence on the Nile River (%)	State
96.4	Egypt
15.4	Rwanda
11.9	Sudan
6.6	Kenya
2.8	Burundi
2	Ethiopia
1.3	Tanzania
0.3	Uganda
0.08	D. Congo

Source: World Bank (2007) World Development Indicators. pp. 14–17 economic pressure on Egypt and the Sudan. Moreover, Ethiopia has not hesitated to show that its abundant water resources are a gift that can be exploited" [44, 45].

This was because of some of the concepts that had historically prevailed in the minds of the Ethiopians since the age of their ancient emperors. For centuries, myths about the ability of the emperors of Abyssinia to divert the waters of the Nile from Egypt had taken place. In the Middle Ages, the belief among the rulers of the Christian empire in Ethiopia and among the rulers of the Muslim world and the Western Christian world increased about the Abyssinian rulers' ability to divert the waters of the Nile. This historical and hostile legacy had a significant impact on the relations between Ethiopia and Egypt since Egypt represented the Arab and Islamic world as well [46].

In 1268, there were many manuscripts indicating that the Ethiopian emperors were able to punish Egypt by preventing the Nile water through their religious and spiritual power. They also took advantage of drought periods and lack of water flood to attribute them to their strength and ability to punish Egypt.

Hurst reported that there have been erroneous reports about the diversion of the Blue Nile to the Red Sea, and hence Egypt would turn into an arid desert, he says:

> This nonsense brings back to mind the idea that prevailed in the Middle Ages when the famine swept Egypt. The minds of the Egyptians were obsessed at that time that the Abyssinians diverted the direction of the Blue Nile. The governor of Egypt, then sent an ambassador with many gifts to the king of Abyssinia seeking to return the river to its original course. In fact, all this talk is nonsense since the diversion of the Blue Nile requires the same work and effort that the diversion of the Rhine to the Adriatic through the Alps would require [47].

In this regard, historical references indicate that the rulers of Abyssinia had always used the Nile water issue as a means of pressure against Egypt, especially with regard to the good treatment of the Copts [46]. Furthermore, under the rule of "Dawoud ibn Yusuf" King of Abyssinia (1,381–1,411), he did not only threaten to divert the waters of the Blue Nile but launched an attack on the Egyptian borders, thus reaching Aswan and taking advantage of the state of chaos experienced by the country during the reign of the Sultan "Barkouk Al-Mamlooky" [48].

The European powers took an interest in this idea and made use of it, especially after the defeat of the Mamluk forces in 1443 AD in "Adl" battle. The purpose was to establish a large Christian force in Ethiopia to face the great Islamic force in Egypt. In many cases this led to rising political issues between the Near East headed by Egypt and the Christian empires in the West. Consequently, there emerged an intellectual-religious and cultural heritage that makes Ethiopia a constant source of threat to Egypt through the Nile waters. This idea was rooted in the minds of the Ethiopians and the Egyptians alike. Moreover, later on this was reflected on the policy of both sides toward each other, and, in turn, Ethiopia gained political power from this ancient idea.

In 1680, the Christian Ethiopian King "Takla Haymanot" threatened the Egyptian ruler at that time saying that:

> The Nile would be sufficient to punish you since God had placed in our hands its fountain, lake and development. Hence, we can use it to harm you.

In addition, some historical documents revealed that the King of Abyssinia, in the early eighteenth century, had sent a threatening message to the Ottoman ruler of Egypt in which he stated:

> The Nile alone is a sufficient means to punish you as God made the source of this river and its flood under our authority. Hence, and we can make use of this river in a way that would inflict harm on you [49, 50].

By the beginning of the nineteenth century, Ethiopian rulers had no satisfaction with the extension of Egyptian influence in the Sudan and its annexation of parts which Ethiopia claimed to be its own. In addition, these rulers learned of Muhammad Ali Pasha's intentions to annex their country to his kingdom, all of which led to further strained relations between Egypt and Ethiopia. The unrest was exacerbated by the encroachment of the Ethiopian tribes on the borders of the Egyptian administration in the Sudan bordering Ethiopia. This was also exacerbated by the looting encouraged by Ethiopian rulers with the aim of creating trouble for Egypt and destabilizing its military position in these areas [51, 52].

This idea continued in the twentieth century. In 1935, after the Italian occupation of Ethiopia, Britain worked to fuel this inherited idea to ensure Egypt's support for her in her position against Italy and to prevent it from using the Suez Canal. The Egyptian public opinion was affected by this issue, and there became a belief in the minds of Egyptians that Ethiopia can prevent the flow of the Nile water into Egypt [53, 54].

The follow-up of Ethiopia's historic positions concerning the waters of the Nile reveals that Ethiopia has historically been suspicious of Egypt and the Sudan and has been watching them with great caution. It has also been constantly filing protest warrants against them claiming its right in the Nile waters [55, 56].

The Ethiopian behavior can be understood in the light of its constant declaration of non-compliance with any agreements on the Nile waters that were concluded prior to its independence. Moreover, Ethiopia also declared its absolute rejection of the 1902 Agreement signed between Britain and Ethiopia during the reign of Emperor Menelik II [57], despite the fact that the Agreement concerned the demarcation of the borders between Ethiopia and the Sudan. Under Article (1) of that Agreement, Ethiopia obtained parts of eastern Sudan which became a subsidiary of Ethiopia. However, Ethiopia renounces the 1902 Agreement because of Article (3) which states that [58, 59]:

> His Majesty the Emperor Menelik II, King of Kings of Ethiopia, engages himself towards the government of His Britannic Majesty not to construct or allow to be constructed any work across the Blue Nile, Lake Tana, or the Sobat which would arrest the flow of their waters except in agreement with His Britannic Majesty's Government and the Government of Sudan.

5 The Historical Development of GERD: From “Border” to “Renaissance” Dam

The Ethiopian Renaissance Dam was known as the “Border” Dam in the American study of the Blue Nile Basin in Ethiopia in the 1960s. In the fifties of the last century, specifically after the July 1952 revolution in Egypt, when Egypt decided to build the High Dam, it was faced by Ethiopia’s strong opposition. It stressed its right as an upstream State to be taken into consideration in the establishment of the High Dam. Subsequently, Ethiopia made an Agreement with the USA to conduct comprehensive studies on the Nile in Ethiopia for establishing possible dams, agriculture, and electricity generation [60].

It is clear that the international environment had a strong impact on regional interactions in the Nile Basin during the Cold War era. The Renaissance Dam (formerly the Border Dam) appeared in the studies provided by the USA side to Ethiopia to exploit the waters of the Blue Nile. Such studies were part of the American policy to put pressure on the Egyptian government. At the same time, the ideological rapprochement between the USA and Ethiopia during the 1950s and 1960s had an important role to play in strengthening their relations. This had a negative impact on their relations with Egypt, because the position of the American administration – at that time – was hostile to the national socialist policies adopted by the Egyptian President “Gamal Abdel Nasser” [61].

During the reign of Emperor Haile Selassie, Ethiopia exploited the existing state of political tension between Egypt and the USA at that time especially after Egypt announced its intention to build the High Dam. Then, Ethiopia cooperated with the US Bureau of Reclamation (USBR) in order to conduct the first integrated study on the rational exploitation of Blue Nile waters in Ethiopia [62]. Indeed, the US government agreed to the Ethiopian request to cooperate with it to conduct a comprehensive study of the Blue Nile Basin. An official agreement was signed between the two governments in August 1957, and a geological survey of the Ethiopian plateau began to propose the establishment of a number of dams on the sources of the Nile. These studies lasted for 5 years between 1958 and 1963 within the framework of a research project entitled “Cooperative Program of the United States of America and Ethiopia for the Study of the Blue Nile Basin” [63].

The study ended with a comprehensive report on the hydraulic situation and water quality in addition to the shape of the Earth’s surface, the geology and mineral resources, underground water, and the soil. The report had also made an evaluation of the socioeconomic status of about 35 sub-basins [64]. The final study was published in 1964 in seven volumes consisting of a major report entitled “Land and Water Resources of the Blue Nile” in addition to six other complementary supplements [65].

The final report of the US Bureau of Reclamation (USBR) in 1964 included a comprehensive assessment of irrigation and energy development projects in the Blue Nile Basin in Ethiopia. This report was based on a comprehensive study of the potential reclaimed land, water resources, and their uses for power generation from the Blue Nile Basin [66]. The US Bureau identified 26 dam sites. The report included the implementation of 33 irrigation and power generation projects on the Blue Nile Basin and its branches (14 irrigation projects, 11 power generation, and 8 combining both). These projects aimed at irrigating five million acres. This can be shown in Fig. 4 [67–70]:

Studies also concluded that four large dams can be constructed on the main Blue Nile (Karadobi, Mabil, Mandaya, and Border dam, later "Renaissance") with a total storage capacity of 50–81 BCM which is roughly equivalent to the annual revenue of the Blue Nile [71, 72] (see Fig. 5).

Regarding the impact of these projects on the Nile water, specifically on Egypt's water quota, the Blue Nile study indicated that irrigation of the proposed land will consume about 6 BCM annually [73].

Ethiopia has exploited the fragile political situation of the Egyptian state after the January 2011 revolution.

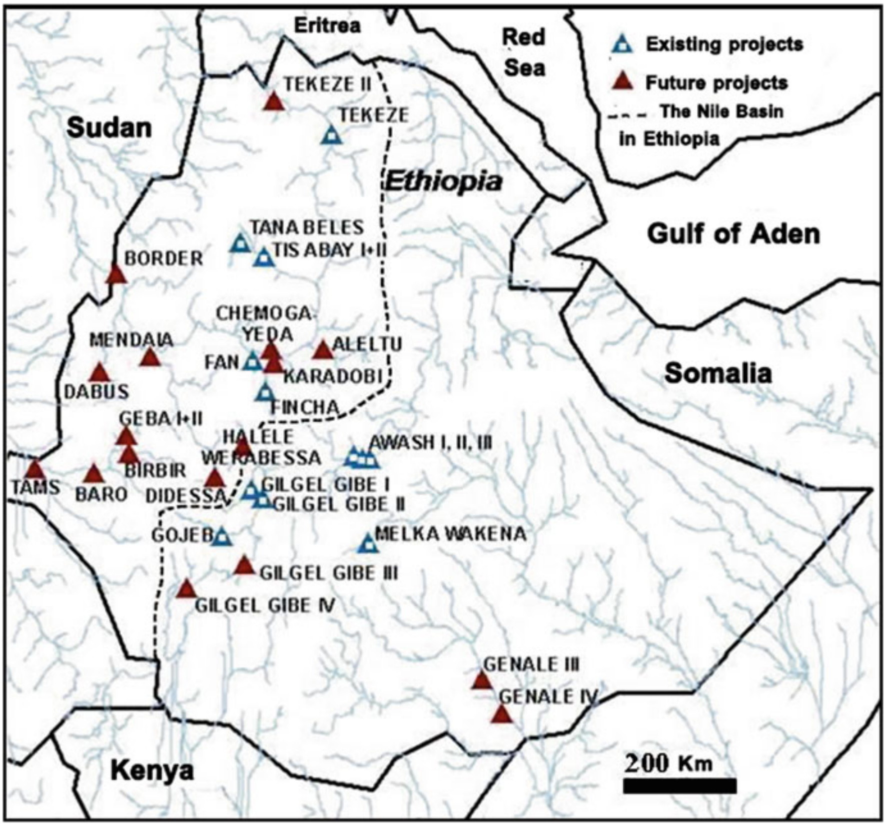

Fig. 4 Proposed water projects on Blue Nile from the Office of American Land Reclamation (1958–1964) [67]

Fig. 5 The four dam sites on the Blue Nile in Ethiopia. Source: http://egyptianchronicles.blogspot.com/2013/06/cairo-universitys-report-on-ethiopias.html

In less than 2 weeks after the project was renamed the Millennium Dam, the name was changed for the third time in the same month. Namely, on April 15, 2011, the Ethiopian Cabinet announced the new name of the project to be the Grand Ethiopian Renaissance Dam [74]. Thus, the name of the dam was changed three times in only 45 days, and each time it was a more popular name. Therefore, it was natural that the change in the name of the dam was accompanied by a steady increase in the specifications of the technical project. In terms of the height of the dam and its storage capacity, it changed from 11.1 BCM, according to the American study, to 145 m with a capacity of 62 BCM according to the Ethiopian Minister of Water and Energy. Then it increased to 67 BCM in the statements of the Ethiopian Prime Minister, then to 70 BCM, and finally to 74 BCM in 2012 [75, 76].

Following the revolution of January 25, 2011, Ethiopia modified the technical specifications of these four dams raising their storage capacity to 200 BCM instead of 50 BCM. This act is, indeed, a flagrant challenge to Egyptian water interests and extremely dangerous to Egyptian water security.

6 GERD and the "No-Harm Rule"

The construction of water dams on international rivers requires discussing the legal dimensions of these dams and how they affect other countries bordering the international river.

The Nile River derives its particularity as the most extensive river among its counterparts around the world, and the current data indicate that it will also be the river that will spearhead international conflicts over water.

In view of the legal dimensions of the GERD, the dam raises the issue of international legal principles relating to international rivers, as well as to water projects on the international river. Among the most important principles are [77, pp. 661–664]: "the no-harm rule, protection of the acquired historical rights, prior notification, international cooperation, equitable and reasonable utilization, peaceful settlement of disputes, non-abuse of the use of the rights, and good neighborliness."

The "no-harm" principle is one of the most important customary rules of international law, which in turn has become a binding legal basis after being adopted and emphasized in Article VII in the UN Convention on the Law of the Non-Navigational Uses of International Watercourses in May 1997.

It thus became an international legal norm for all states, whether or not they were signatories to this Agreement. The text of the article was as follows:

> Watercourse States shall, in utilizing an international watercourse in their territories, take all appropriate measures to prevent the causing of significant harm to other watercourse States.

The drafting of this Agreement came after a long argument raised by a number of the upstream countries, headed by Ethiopia, where there was an objection to include such a text. The upstream countries considered that this text would be incompatible with the realization of States' sovereignty and independence while making decisions on internal projects on the international riverbed. The wording was put in this way to satisfy all parties, since the requirement of no-harm was no longer absolute as a condition was included that the harm would not be a significant one [77, pp. 674–676].

Objectively, away from the approach of exaggeration or understatement, the GERD should be seen as an engineering project, and, then, the principle of "no-harm" can be discussed through reviewing the benefits of the GERD for Ethiopia, Egypt, and Sudan while comparing these benefits with the damage caused by its establishment as given in the following subsections:

6.1 GERD Benefits

1. Ethiopia’s major benefit from the dam is the production of hydroelectric power (5,250 MW or 6,000 MW as announced later), which is nearly three times the energy currently used [78].
2. Providing water to the residents of the “Bani Shankul Gomez” area throughout the year, some of which may be used for drinking and limited irrigated agriculture.
3. Controlling the floods that affect the Sudan, especially at the “Rusairis” Dam.
4. Storing the Blue Nile silt, which is estimated at 420 BCM annually, which prolong the life of the Sudanese dams and the High Dam [79–81].
5. Reduced evaporation due to the existence of the dam lake at a height of 570–650 m above sea level (compared to evaporation in the high dam lake, 160–176 m above sea level).
6. Relieving the load of stored water at the High Dam Lake, which causes some weak earthquakes [82, 83].

6.2 GERD Disadvantages

1. High cost estimated at 4.8 billion US dollars. This cost is expected to reach 8 billion US dollars due to geological and topographical defects in Ethiopia.
2. Displacement of about 20–30 thousand citizens from the lake area.
3. Limited lifespan of the dam, which ranges from 25 to 50 years as a result of the severe siltation (420 thousand cubic meters per year) in addition to the consequent large problems for power turbines, and the gradual decrease of the dam’s efficiency [84, 85].
4. Increased opportunities of the dam’s collapsing as a result of the geological factors and the Blue Nile water rush speed, which in some days (September) amounts to more than half a billion cubic meters per day and from a height of more than 2000 m toward the level of 600 m at the dam. If this happens, the greatest damage will inflict the Sudanese villages and cities, especially Khartoum, which may be swept away in a tsunami-like manner [86, 87].
5. Increased opportunities of earthquakes in the area where the reservoir is formed due to the weight of water that was not previously present in the area, which may reach 74 billion tons. This weight is distributed over the whole lake surface of 1,800 km^2 in addition to the weight of the rock dam. Another measure is soil stress which is measured by the weight of the water column on the flat meter from the bottom of the lake. In the case of GERD, the maximum stress is 145 tons per square meter from the lake bottom. All in a shaky rocky environment [88].
6. Sudan losing silt fertilizing the agricultural land around the Blue Nile, which is the main source of plant nutrition as the Sudanese are not accustomed to using fertilizers.

7. Contamination of the Dam Lake water due to its storage above rocks rich in minerals and heavy elements [89, 90].

At the Egyptian domestic level, experts and specialists stressed that the dam has great risks on all aspects: water, agriculture, environment, economic, social, and electrical. The details of the dam and its negative effects on Egypt can be identified through the report issued by the Technical Committee for the Dam Assessment, which was issued in May 2013 [91].

Studies confirm that GERD will threaten Egypt's water resources (for more details, see [85, 92–96]) and will have significant negative impacts on Egypt's agricultural sector (for more details, see [97–102]) and the electricity generation sector, in addition to its negative impacts on Egypt's high dam (for more details, see [103, 104]).

The abovementioned facts undoubtedly confirm that GERD will cause serious damage to the downstream State (Egypt), both when it is completed and filled or in case of a collapse scenario. This, in turn, confirms that GERD does not agree with the principle of "no-harm" as one of the governing principles of international rivers [105, 106].

Therefore, the Eastern Nile States should cooperate and coordinate among themselves on filling and operating policies, in order to take advantage of the electricity generated by the dam [107].

7 GERD: Is It the Bridge of Ethiopian Hegemony Over the Nile?

The study presents a political and strategic reading of the question of GERD from a scientific and objective perspective, based on the analysis of Ethiopia's hydropolitical behavior on GERD. In other words, what are Ethiopian goals behind the construction of GERD?

The analysis of the Ethiopian situations in regard to the GERD clarifies the Ethiopian politicization of the Nile waters issue in order to achieve political and strategic objectives, along with the developmental goals (for more details, see [108–110]).

The following points affirm this conclusion:

1. *Ethiopia seeks to impose a hydropolitical hegemony on the Nile Basin:* Which means transforming the hydro-hegemony into hydropolitical and hydrostrategic since it realizes that it contributes the largest amounts of water into the Nile [111].

   Ethiopia is aware that it has a hydraulic advantage over the Nile Basin based on the hydraulic and topographic facts of the Nile. It is known that 33.2% of the Ethiopian State is located within the geographical area of the Nile Basin and that 11.7% of the total Nile basin is located in the Ethiopian territory. Furthermore, the Ethiopian highlands contribute about one third of the rainfall on the Nile (which is about 590 BCM per year of the total rainfall estimated by 1,661 BCM annually). More importantly, 84.5% of the Nile's total annual water revenues flow from the Ethiopian sources (71 BCM of 84 BCM). Naturally, then, the Ethiopian State is aware of the fact of the hydraulic situation which saves it a degree of "hydro-hegemony." Therefore, Ethiopia feels that it has the greatest credit over the Nile River water revenues [112].

Therefore, it seeks to interpret this hydro-hegemony into hydropolitical and hydrostrategic on the regional system of the Nile. The GERD is one of the mechanisms to achieve this objective on the Eastern Nile Basin [113, 114].

As an assertion of the hydropolitical hegemony, Ethiopia intended to build three other dams on the Blue Nile to have a full control over the flowing waters reaching Egypt. Those dams are "Mendiya," "Bako Abo," and "Karadobi," aiming to raise the water level in Lake Tana (upstream of the Blue Nile) or to change the River course whenever desired [115].

Ethiopia has amended the technical specifications of the four dams so that their capacity reached 200 BCM instead of 50 BCM, in a clear challenge to the Egyptian water interests and as a severe threat to the Egyptian water security.

In general, the statements of Ethiopian officials confirm that Ethiopia is seeking to build up these hydropower projects to take advantage of its natural, topographic, and hydroelectric potential to generate electricity and expand its electricity supply to its citizens. Thus, achieving economic savings will help it meet the overall development requirements through the proposed electricity linkage projects with the Sudan, Djibouti, Yemen, Uganda, and Egypt [116].

Ethiopia concealed objectives beyond the establishment of those dams to achieve a hydropolitical hegemony over Egypt and put it under a water siege, and consequently, placing it under a political and strategic siege in order to impose political and strategic settlements on Egypt and change the strategic balance interactions in the Nile Basin regions so that the leadership of the region becomes fully Ethiopia dominated [117–119].

As an evidence of Ethiopia's objective, the height and size of the Nada dam were maximized more than needed although this has affected the efficiency of the dam to generate power [120].

In the US study in 1964, the dam specifications were more appropriate, more efficient, and cheaper.

The decrease in efficiency is due to the exaggeration of the dam's height and storage capacity. This proves the desired political hegemony of the dam. The total investment of the current project could be reduced by nearly 50% by building a smaller dam with higher efficiency and less risk to the Sudan and Egypt, especially in the event of the failure or collapse of the dam due to the aforementioned geological reasons. This can be illustrated by Fig. 6 [121, 122].

However, the Ethiopian National Panel of Experts (NPoE) confirmed that the Egyptian political allegations about GERD are not true, asserting that these statements are issued only by those – who the committee described – "Egyptian exaggerating experts" [123, 124].

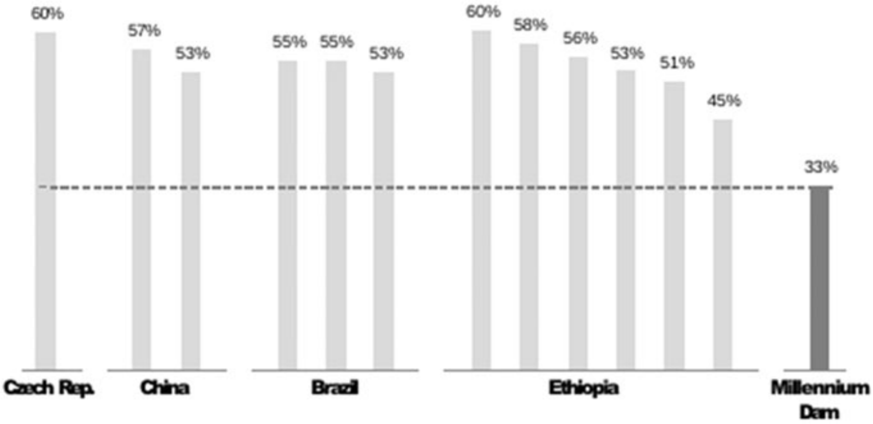

Fig. 6 Electricity generation efficiency in GERD [121]

These Ethiopian statements can be refuted based on scientific studies prepared by Asfaw Beyene – a professor of mechanical engineering and director of the renewable energy in San Diego State University, USA – who asserts that there is an unjustified exaggeration of the dam size technically. He wonders: “what is the reason to build a dam with that height and with that capacity if its purpose is only power generation” [124]. It is worth mentioning that he is an Ethiopian national.

In another study, prepared by Beyene, he stated that the Renaissance Dam is useless as far as electricity is concerned since it has a low efficiency to generate power due to its exaggerated size and height [125].

Studies confirm that the GERD could have been a useful project for all the countries of the Eastern Nile Basin if its technical specifications had been changed, both in terms of height, size, and storage capacity; in this case, it could be a project shared by the three Eastern Nile states to benefit from its revenues according to the benefit-sharing approach [126, 127].

This asserts the notion that the Renaissance Dam – with these technical specifications – is established to harm the Egyptian interests and put severe pressure on it to pave the way for the Ethiopian hydropolitical hegemony.

2. *Ethiopia adopts a fait accompli policy*: Since the end of the 1950s, the Ethiopian policies expressed a desire to impose a fait accompli policy through a chain of projects which it started in cooperation with the US Bureau of Reclamation. There was an increase in the number of plans to establish dams on the Nile tributaries during the last decade. Ethiopia completed the Tekeze Hydropower Dam and Belesse Hydropower Dam. Later it started the establishment of the Renaissance Dam without any notification to the downstream State (Egypt) [128].

   This policy was clearly exposed when a trio committee was formed to evaluate the dam in 2012. The Ethiopians insisted that the primary documents should state that the “Renaissance Dam is under construction” and refused the suggested phrasing presented by Egypt and Sudan completely. Their phrasing stated that it is “a potential dam.” The Egyptian negotiator was forced to accept the Ethiopian wording.

The Ethiopian side waged a physiological war when sending notes either via its officials or diplomats in an attempt to convince the Egyptians that it should accept the status quo which is that the dam will be built regardless of the recommendations of the International Tripartite Committee [2, 129].

As part of the policy of fait accompli, Ethiopia sought to thwart the negotiations and talks under the Technical Committee for the assessment of the effects of GERD, which began in 2012 and which included ten technical experts (two from Egypt, two from the Sudan, and two from Ethiopia. In addition, the Committee included four international experts from Germany, the USA, France, and South Africa). This committee was formed to discuss the technical issues related to the construction and operation of GERD. Ethiopia has succeeded in spreading tension to the Egyptian side and dispersing its effort into details that are not worth discussing. The Ethiopians have also succeeded in breaking up the fundamental issue of “the international responsibility of Ethiopia” for not complying with the requirement of “prior notification” and for breaching one of the principles of the international law on good neighborliness and not causing harm and consequently falling under international responsibility [130, 131].

Furthermore, Ethiopia has managed to undermine the issue mentioned and lured the Egyptian negotiator to unimportant partial points. The aim was to achieve an Ethiopian goal of prolonging the negotiations in the context of the “Ethiopian strategy to negotiate” based on gaining time, procrastination, and intransigence. Ethiopia has also followed the strategy of deception, nontransparency, and concealment of information and data during the Tripartite Commission’s talks and negotiations. Thus, the failure of GERD negotiations is due to the fact that they have turned into a “zero-sum game.”

The Egyptian side has fallen victim to this “planned lure on the Ethiopian side.” The Egyptian side also made a mistake of not taking advantage of the final report results of the International Committee for the Study and Evaluation of GERD issued in May 2013 which confirmed the negative impact of GERD on Egypt. Moreover, Egypt did not move politically in the appropriate manner to market the results of that report at the regional and international levels by showing GERD danger on Egypt in all aspects whether economic, hydrological, electrical, social, or environmental.

Ethiopia’s “policy of imposing a fait accompli” in the Nile Basin regional system may lead it to the adoption of ill-considered mechanisms and tools. One of the proofs is the negative impacts that GERD will afflict on agriculture in the dam’s area (Bani Shankul-Gomez) [132–134]. Studies confirm that the lake that will be built in front of GERD will lead to the dumping of about half a million acres of forest land and irrigated agricultural land. These lands are difficult to compensate because of the geological characteristics and mountainous and rocky nature of this area in addition to the absence of other close irrigable and arable areas [135–137].

Figure 7 illustrates the arable and irrigable areas in the Blue Nile Basin area in Ethiopia. This figure shows the limited arable and irrigable areas in western Ethiopia, i.e., in the areas of the Blue Nile Basin [138, 139].

3. *The Ethiopian moves are individual and unilateral and lack coordination with the Basin states and Egypt:* In specific since it does not believe in the importance of the “prior notification condition” before the execution of its water projects on the Nile tributaries and insists that it has an absolute right to deal with the section of the River running on its territories freely without any cooperation with Egypt or any other basin state [140].

In this context, Professor Zewde Gebre-Sellassie at Addis Ababa University asserted in a lecture delivered during the conference arranged by Tel Aviv University in May 1997 that the Ethiopians believe – since 1950 – that they have a right to the waters of the Nile; therefore Ethiopia has the right to execute any project contained in the study of the US Bureau (1964) to meet its needs [141].

While professor Harold G. Marcus – from Michigan University – dealt with the subject of the Ethiopian water projects in a lecture delivered in the same conference, where he mentioned that the Ethiopians threatened many times to

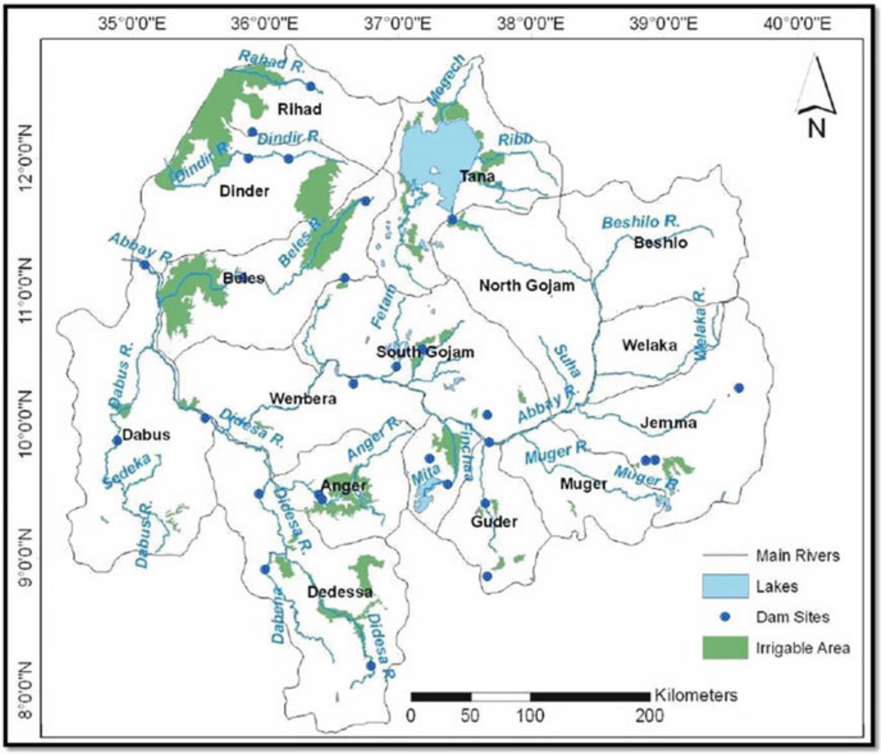

Fig. 7 Cultivable areas of the Blue Nile Basin in Ethiopia [138, 139]

execute projects that can prevent the flow of the Blue Nile waters so that they can push Egypt to give some concessions, the technology needed for this was not yet available, but emperor Haile Selassie hoped to execute these projects to generate the electricity much needed for the African development projects and sell the water to Sudan and Egypt.

Yet, due to the Ethiopian weakness, Haile Selassie did not manage to obstruct the Nile waters treaties. Marcus mentioned that the emperor awarded an engineering office in New York to study the possibility of building a dam in Ethiopia on Lake Tana to control the flow of the Blue Nile for the purpose of power generation and to irrigate many areas in the State [142].

The hostile side of the Ethiopian hydro-politics toward Egypt lies in the fact that it does not call only to adopt the "Harmon theory" but call the Nile a "transboundary river" [143] instead of calling it an international river. The latter is more accurate as stated in all the agreements on international rivers signed by many states starting from the Barcelona Agreement regarding navigation in the international rivers (1921) then the Helsinki Doctrine on the international rivers basins (1966), and finally the Convention on the Law of the Non-Navigational Uses of International Watercourses (1997) [144].

The term "transboundary river" – as adopted by Turkey and Ethiopia – constitutes a political danger since the implication of the term is far dangerous than it seems.

Explicitly the River is internal, so it is subject to the absolute sovereignty of the upstream State but it crosses the borders of this state, but this crossing does not affect or limit the absolute sovereignty of the upstream State on it [145] (it is worth mentioning that the term "transboundary river" was mentioned in the summary of the technical report issued by the technical commission which was assigned to evaluate the effects of Renaissance Dam, and the Egyptian side had no reaction toward this serious issue).

Ethiopia's individual and unilateral moves and its reluctance to coordinate with the Nile Basin states, especially Egypt, may adversely affect not only the pattern of hydropolitical reactions in the basin but may also sometimes damage Ethiopia's own interests. This is evidenced by the negative effects of GERD on the mining reserves in Ethiopia. The lake that will be formed in front of GERD will submerge some of the most important mining areas in the country, which host major stocks like gold, platinum, iron, brass, and some of the stone pits [146, 147] (see Fig. 8).

It is noteworthy that Ethiopia is not rich in minerals except for two regions: one in the south on the border with Kenya and the other – the richest in minerals – in GERD area. Thus, Ethiopia will lose more than half of its mining balance drowned by GERD Lake [148, 149]. This is illustrated as Fig. 8.

4. *Ethiopia aims to change the hydropolitical and hydrostrategic balance in the water regional system of the Nile Basin*. Through its water politics in the Nile Basin making an "initiator" of itself or an "actor" who does the act and the others are "subjects" or the ones who react since Ethiopia is the one that identifies the

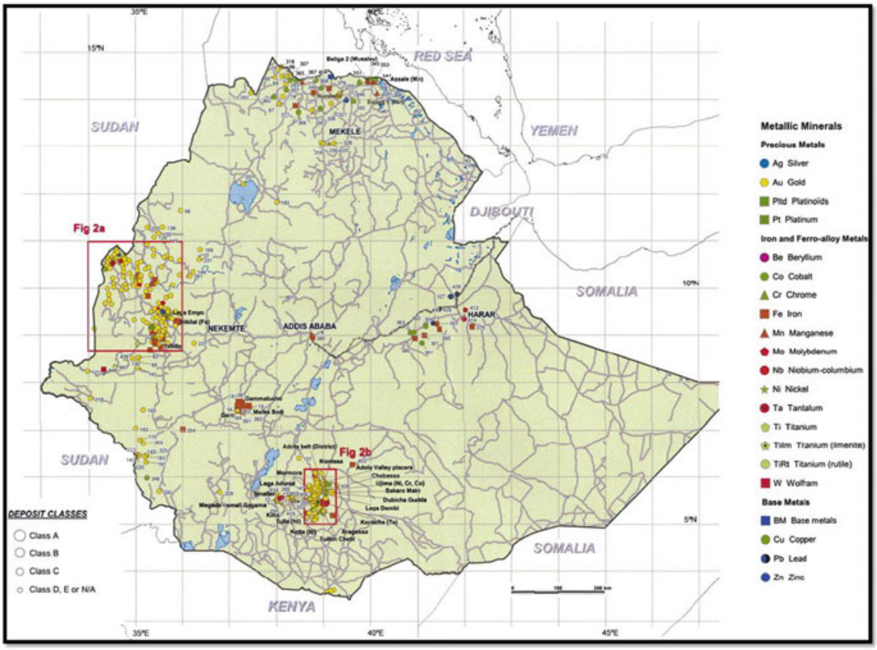

Fig. 8 Mineral-rich areas in Ethiopia in the Blue Nile Basin. Source: http://www.sciencedirect.com/science/article/pii/S0899536203000484

"risks" in the Nile Basin and decides – in the time appropriate for itself – which dams to build.

It also accuses the upstream Egypt with "the desire to wage a water war" and "incite Eritrea against Ethiopia." In addition, Ethiopia decides – solely – and in the time it wishes that the "Egyptian interests will not be harmed due to the Ethiopian dams" [150–152]. In other words, Ethiopia desires to establish a new reality where it becomes "the regional actor" or the "regional dominator" on the regional system of the Nile Basin [153, 154]. To establish this new reality and in order to achieve a regional hydropolitical hegemony, it alleges that Egypt and Sudan obtain 90% of the River waters and calls for "equal" allocation [155].

On the other hand, Egypt replies by asserting the principle of fair and just use of the River resources. The amount of rain on the Nile Basin exceeds 1,660 BCM/year; Egypt and Sudan obtain 84 BCM only, which equals 5% of the total amount, while Ethiopia and other upstream states obtain the green waters which are reserved underground benefiting the natural meadows. The rainwater which falls on Ethiopian areas located in the Nile Basin is approximately 900 BCM.

Ethiopia claims that it has the right to obtain water quotas equal to those obtained by Egypt due to the number of its population since it is equal to that of Egypt's. But those allegations are groundless since Egypt is the only Nile state whose citizens live in the Nile Valley (96% of the Egyptians). Therefore, it depends on the Nile almost completely, while only 39.5% of the Ethiopians live in the Nile Basin while the rest live in the Basins of other rivers running within its territories.

On the other hand, in its reply to Ethiopia's alleges that Egypt declared that it does not obstruct the development in any basin state including Ethiopia, it did not object the Tekeze Dam which was built in 2009 in Ethiopia with a capacity of 9 BCM and did not object the Tana Pelace power generation project which was executed in 2010 since both have a limited impact on Egypt [156–158].

5. *Ethiopia employs the regional and international contexts to achieve its strategic objectives*. On the international level, it employs the strategic conflict of interests with Egypt in Africa, on the one hand, and the current superpower (the USA), on the other. In light of the US attempt to achieve geostrategic hegemony in the African continent through its alliance with some regional powers, namely, Ethiopia, Ethiopia under Prime Minister Meles Zenawi succeeded in the last two decades to present itself as a potential ally that could protect the American interests in the Horn of Africa. This endangers Egyptian interests in the Nile Basin, especially with the absence of any strong strategic relations between Egypt and any other superpowers that can be employed for political maneuvers with the USA [159].

   On the regional level, Ethiopia succeeded – to some extent – to establish which it calls a "special relation" with Israel. Hence, it employs the Israeli hegemony over the Middle East with the help of the USA, exploiting the Egyptian distraction due to the internal and external files doubling the negative consequences and impacts on the hydropolitical transactions in the Nile Basin [160, 161]. Consequently, Prince Khalid Ben Sultan – the director of the Arab Council for water – summarized the hydropolitical situation of the Renaissance Dam saying:

   > The dam will cause a deliberate harm to the Egyptian rights in the Nile and will jeopardize the water potentialities of both Egypt and Sudan. Egypt will be the main loser from the establishment of the Renaissance dam because it possesses no water alternatives similar to the rest of the Nile Basin states. The establishment of this dam is a political hostility not an economic gain [162].

8 Conclusion and Recommendations

Ethiopia's announcement of the construction of GERD a few weeks after the Egyptian revolution and the commencement of groundbreaking in April 2, 2011, was only one of the intensive episodes of Ethiopian action to realize the dream of water domination over the Nile Basin, which had haunted the Ethiopian emperors for centuries. This Ethiopian dream has been renewed recently. Ethiopia is seeking to achieve it through the establishment of a number of dams on the Blue Nile, undeterred by the impact of those water projects on the Egyptian water interests or water security.

The analysis of Ethiopia's conduct on GERD negotiations reveals that it seeks to consume and waste time in a planned manner while not making any concessions in addition to spreading contrived tension to the Egyptian side. Moreover, Ethiopia tends to divert the Egyptian side's efforts into unimportant details while undermining the fundamental issue of Ethiopia's responsibility to build a huge dam without prior consultation with the downstream State, Egypt.

This Ethiopian behavior confirms that Ethiopia's stated goals of building GERD are development. However, there are undeclared political and strategic objectives such as the hydropolitical hegemony on the Nile. This is evidenced by Ethiopia's attempt to impose a new fait accompli, its unilateral moves and attempt to change the hydropolitical and hydrostrategic equilibrium in the Nile Basin regional water system, even if it was at the expense of others' interests. It is also evident that Ethiopia makes use of the international and regional contexts to achieve its strategic objectives.

The analysis of hydropolitical behavior of Ethiopia on GERD, as presented, confirms the validity of the hypothesis from which the study was initiated. This valid hypothesis proves that there is a correlation between the Ethiopian intransigence and the insistence on building GERD with the current specifications. Subsequently, the aim is to enable Ethiopia to have political control over the Nile and hence damaging the Egyptian national and water security. Thus, the study has verified the validity of its scientific hypothesis.

The current and future water projects in Ethiopia or other Nile Basin countries can be a means of rapprochement between the basin countries if they are dealt with by the win-win approach. The aim of such approach is that the various basin countries should agree on development projects that generate energy for the source countries. This should be in a way that does not affect the Egyptian and Sudanese water quota while at the same time realizing the interests of all the peoples of the Nile Basin [163]. However, this cooperative approach is subject to acceptance by the source countries of the requirement of prior notification before the implementation of any water projects.

Conversely, Ethiopia's rejection of the "prior notification condition" and the invocation of absolute territorial sovereignty over the part of the river in its territory may open the door to further conflicts in the Nile Basin [164].

The hoped-for means of cooperation in the Nile Basin will depend on a number of factors:

First, success in breaking the current water situation and breaking the zero-sum game concerning some controversial issues in the Entebbe Agreement as well as getting out of the zero-sum game of GERD negotiations.

Second, the multidimensional integrated vision of cooperation and integration among Nile states to benefit beyond the river. This can be achieved by focusing on the prospects of cooperation and achieving benefit-sharing. It can also be achieved by expanding cooperation to include development sectors in all political, security, economic, cultural, and social fields and not to be limited to cooperation in the water sector. The purpose is, then, to realize the ambitions and aspirations of the peoples of the Nile Basin countries in development, stability, and modernization.

Third, to move toward interconnection projects between Nile states. This will serve as the most effective complementarity mechanism to mitigate the frantic trend of some of the basin countries toward building dams. Electric linking projects will also serve as the locomotive for integrated work between the Nile Basin countries and their peoples.

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Impact of the Grand Ethiopian Renaissance Dam (GERD) on Gezira Groundwater, Sudan

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Contents

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Abstract The Gezira area has one of the most massive agricultural projects in the world. Groundwater is one of the most critical water resources in Sudan. About 80% of the people in Sudan depend mainly on groundwater. The Grand Ethiopian Renaissance Dam (GERD) is under construction on the Blue Nile at 15 km from the Sudan's border, creating a reservoir of 74 km^3. The environmental studies of the GERD effect on Egypt and Sudan are vague. The present paper deals with the assessment of groundwater in Gezira using geochemical analysis, stable isotopes, remote sensing, and GIS. The impact of land use/land cover on groundwater quality was studied using supervised classification techniques of multidates (multitemporal) satellite images. Also, it covers the investigation of water interaction between the surface water and Gezira groundwater aquifer. The surface water includes the White Nile and the Blue Nile that will be controlled entirely by the GERD. If there is a direct recharge from the Blue Nile, the GERD will increase the recharge because it will keep the water in the Blue Nile always at a high level all year, resulting in increasing the seepage to the aquifer. The agriculture will also be all over the year, so water infiltration to groundwater will be increased. The major ions, nitrate, ammonium, heavy metals, and stable isotopes (δD and $\delta^{18}O$) were measured to achieve these goals. The results of hydrochemical data were mapped using ArcGIS 10.3 and Aquachem software. The results indicated that there are no any evidence for the groundwater pollution resulted from the anthropogenic activities in the study area. Although agricultural projects have been started with full capacity, since 1960, the pollution traces were not detected. The stable isotopes of the ^2H and ^{18}O confirmed that the groundwater of the Nubian aquifer in the study area is recharged from the Blue Nile through the Gezira aquifer. Moreover, away from the Blue Nile, the influence of recharge is negligible, but the water of the Nubian aquifer still mixed with water of heavy isotopic composition. The chemical and physical characteristics of groundwater indicate that the GERD will increase the recharge because it will keep the water in the Blue Nile always at a high level all year, resulting in increasing the seepage to the aquifer. The agriculture in Sudan will also be all over the year, so water infiltration to groundwater will be increased.

Keywords GERD, Gezira, Groundwater, Hydrochemistry, Nile, Nubian Sandstone Aquifer, Renaissance Dam, Stable isotopes

1 Introduction

In April 2nd, 2011, Ethiopia began the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile at 475 km northwest of Addis Ababa and 15 km from Sudan's border (see Fig. 1). The GERD will be the largest dam in Ethiopia: 1,800 m long, 155 m high, and with a total volume of 74 km^3 [2, 3]. The dam is located in an area dominated by the Precambrian basement rocks containing granite and metamorphic rocks [3]. The GERD was known as Border Dam in the US Bureau of Reclamation study (1958–1964). The name was changed to "X-Project" in March 2011, and in 2 weeks it was renamed to the "Millennium Dam," and then the Council of Ministers in April 2011 renamed it for the fourth time to Grand Ethiopian Renaissance Dam. There are some advantages of the GERD for Sudan including management of Blue Nile sediments, flood control, providing water flow all over the year, and increasing the efficiency of the electricity production from the Sudanese dams [4].

Currently, there are 2.4 billion people worldwide, who do not use improved sanitation. According to the WHO/UNICEF Joint Monitoring Program for Water Supply and Sanitation, "at least 1.8 billion people world-wide are estimated to drink water that is faecally contaminated" [5].

Groundwater is significant as a source of water for the people in Gezira State, where they depend on about 85% of groundwater for domestic purposes [6]. Gezira area is located between two Niles: the Blue Nile to the east and White Nile to the west. It is bordered by the railway of Sennar-Kosti in the south. Gezira area is triangular in shape and covers an area of about 27,160 km^2. The area is occupied by large agricultural projects, which are called Gezira and El Manaqil Schemes. Although the Gezira area is bordered and restricted from the east by the Blue Nile and from the west by the White Nile, it depends on the groundwater as the primary source for domestic purposes.

The groundwater in Gezira is stored in metal boxes before distribution via tubes to the public, which are checked periodically to meet the standards of water quality and to prevent any health hazards. Also, the higher salinity, especially in the central Gezira at El Manaqil and its neighborhoods, was recorded. Moreover, the absence of observation wells which allow more control and management for the aquifers in the study area is a big problem. This is because of the higher costs of drilling observation and production wells as a consequence of the critical economic situation of the country.

The Gezira occupies most of the Gezira State at the west side of the Blue Nile and a small part of Sennar State in the Gezira area in central Sudan. It is bounded to the east by the Blue Nile. It extends between latitudes 13° 58′ 21.56″ and 14° 51′ 14.59″ N and longitudes 32° 47′ 35.65″ and 33° 40′ 4.44″ E, with an area of about 6,100 km^2.

The Gezira has the significant agro-economic projects in Sudan since 1925. From this point of view, evaluation for groundwater and assessment of the relation between surface and groundwater for sustainable development are strongly

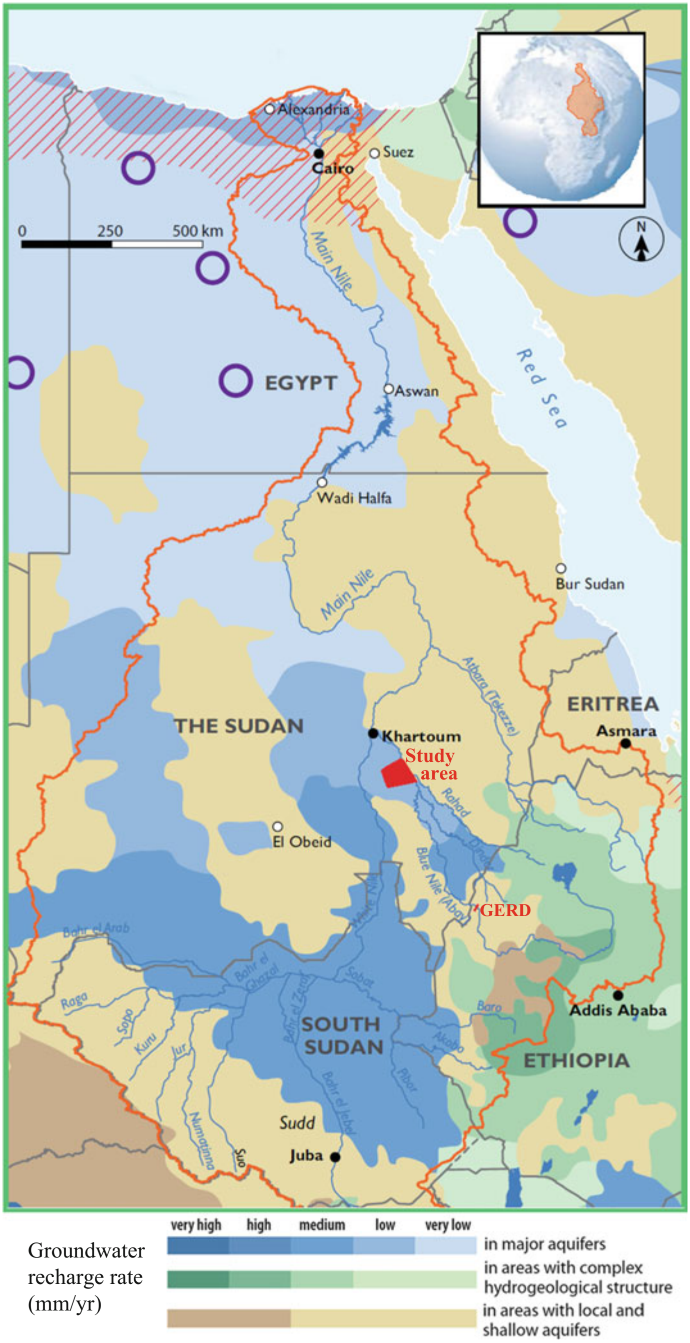


Fig. 1 Location of the study area and Grand Ethiopian Renaissance Dam (GERD) [1]

recommended to protect the main sources of water from pollution resulting from agriculture and other activities.

The present work deals with the following:

1. Geology and physiography of central Sudan (Gezira)
2. Hydrology and hydrogeology of Gezira
3. Hydrochemical properties of the surface and groundwater
4. Suitability and evaluation of groundwater quality for different purposes
5. Evaluation of the effect of land use on the groundwater quality
6. Finding the interactions between the Blue Nile and groundwater in the Gezira area

The Gezira area, central Sudan had been investigated and studied by many researchers in the fields of structure, geology, hydrogeology, hydrochemistry, and physiography; among them are Tothill [7, 8], Shukri [9], Abdel Salam [10], Kheirallah [11], Williams and Adamson [12], Salama [13, 14], Farwa [15], Adamson et al. [16], Omer [17], Schull [18], Magboul [19], Jodat [20], Mohamed [21], Omer [22], Zeinelabdein et al. [23], and Elkrail and Omer [24].

Magboul [19] studied the hydrogeology of the northern Gezira area, central Sudan. He concluded that the transmissivity values of the lower Gezira and Nubian aquifers are 210 and 836.5 m^2/day, respectively. Also, the groundwater quality of the Nubian aquifer is excellent for all purposes, while the groundwater of the Gezira aquifer is suitable for irrigation purposes except in the areas of the higher salinity. Jodat [20] studied the groundwater assessment of the area between Wad Madani and Sennar. She concluded that the hydraulic conductivities in east Wad Madani have the same average for Alatshan and Nubian aquifers. The groundwater quality and hydraulic properties of the aquifers in the area between Wad Madani and Sennar are good.

Elzein [25] concluded that "the water quality of the Nubian and Gezira Formations are saline in some areas, but in other areas, it is of good quality for different purposes". Zeinelabdein et al. [23] detected possible causes of earthquakes in central Sudan using the integrated GIS approach. They concluded that the area is traversed by several fractures and faults. Elkrail and Omer [24] designed a conceptual model for numerical flow simulation, the aquifer potentiality, general groundwater flow direction, and the primary source of recharge at Abu Quta area, Gezira State. They concluded that the river leakage represents 58.0% of total inflow indicating the main source of recharge.

2 Material and Methods

Thirty-nine groundwater samples were collected during the field work in 2013 from the available wells tapping the Nubian Sandstone Aquifer and two samples (wells Nos. 15 and 27) tapping the Gezira aquifer. These two samples of the Gezira aquifer were collected to check them for any pollution possibilities. However, the study of the Nubian Sandstone Aquifer System is the main goal of the present work. Two surface water samples were collected from the Blue and White Niles.

Thirty-one water samples were collected from the available or pumped wells. The collected samples locations were determined using geographic positional system (GPS) (see Fig. 2). They were used to determine the TDS and major ions

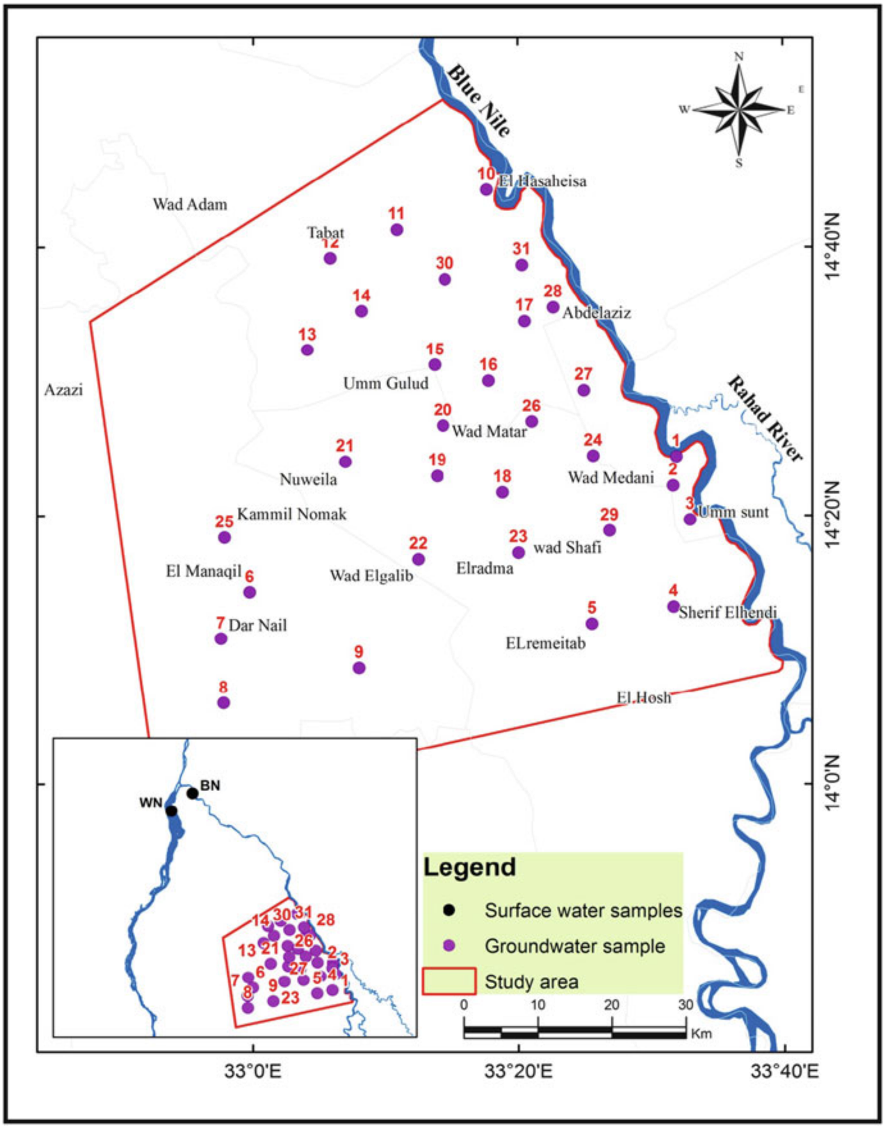


Fig. 2 The location map of water samples in the Gezira area

(i.e., Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, NO_3, Cl^{-}, CO_3^{2-}, HCO_3^{-}, and SO_4^{2-}). The field measurements included the hydrogen ion activity (pH), electrical conductivity (EC), as well as the temperature (T) of water. Besides, ten samples were acidified of six drops of HCl acid to determine trace elements (i.e., As, Cd, Co, Cr, Cu, Fe, Mn, Pb, and Zn). All samples were analyzed in the Central Petroleum Laboratories (CPL) at Khartoum, Sudan. The results are represented as follows: ion concentrations and TDS, which are expressed in part per millions (ppm). Moreover, ion concentrations are also expressed in equivalent per millions (epm) and percentage of equivalent per millions. Temperature (T) is expressed by Celsius (°C) and electrical conductivity (EC) in µS/cm.

2.1 *Normalized Difference Vegetation Index (NDVI)*

The normalized difference vegetation index (NDVI) is considered as the most common method used in different studies for monitoring of vegetation [26, 27]. Land cover and vegetation recognition at the study area were applied by computing the NDVI and the maximum likelihood method of supervised classification. The NDVI algorithm subtracts the red reflectance values from the near-infrared and divides it by the sum of near-infrared and red bands [28]:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED})$$

where NIR and RED are the reflectances radiated in the near-infrared wave and the visible red wave, respectively. For the Landsat 2 MSS sensor, the NIR is band 7 of the wavelength range (0.8–1.1 µm), and the red is band 5 (0.6–0.7 µm), while the NIR and red bands of Landsat 8 OLI are band 5 of wavelength range (0.85–0.88 µm) and band 4 of wavelength (0.64–0.67 µm), respectively. For this purpose, satellite images of different remote sensors were used (Landsat MSS, OLI) to produce land cover and vegetation maps. The satellite images were obtained from the website http://earthexplorer.usgs.gov/ of the United States Geological Survey (USGS), and the acquisition dates are December 24, 1975 and December 07, 1975 for the two scenes of Landsat 2 MSS of row 50 and paths 185 and 186, respectively. Two scenes of Landsat 8 OLI (row 50 and paths 172, 173) and their acquisition dates are November 02, 2013 and October 26, 2013, respectively. In the analysis of the satellite images and the data explanation, the ENVI 4.8 and ArcGIS 10.3 software were used.

2.2 *Stable Isotope Analysis*

Stable isotope analysis is conducted by collecting 12 groundwater samples in 250-mL transparent glass bottle during the field study (July 2013) for the estimation of stable isotopes, deuterium (^{2}H), and oxygen 18 (^{18}O).The samples were sealed and preserved in the cool tank to prevent evaporation and were transported to the laboratory in Cairo by the author.

This analysis was performed at the Central Laboratory for Environmental Isotope and Nuclear and Radiological Regulatory Authority in Cairo. Also, these stable isotopes were determined using an isotopic ratio mass spectrometer (Thermo–Finnigan Delta Plus XL) by equilibration technique. The instrument is linked with an equilibration unit for online determination of ^{2}H and ^{18}O isotopic composition using either H_2 or CO_2 gas under constant temperature (18°C) [29–31]. Platinum rods are used as a catalyst in case of ^{2}H only.

Stable isotope ratios are measured relative to the standard and are expressed in parts per thousand or per mil (‰). The isotope ratio is expressed as δ value or "del value" as it is sometimes called [32].

The following equation defines the isotope ratio:

$$\delta \text{ sample } (‰) = \frac{R_{\text{Sample}} - R_{\text{Standard}}}{R_{\text{Standard}}} \times 1{,}000$$

where, R values refer to isotope concentration ratios, either D/H (^{2}H/H), ^{18}O/^{16}O, or ^{13}C/^{12}C, as appropriate. It depends on the element of interest and δ defined in the equation as, e.g., δ^2H, δ^{18}O, δ^{13}C values. The δ values have been converted to part per thousand or per mil (‰) by multiplying by factor 1,000.

3 Climate Conditions

The Gezira area lies in the semiarid zone of Sudan, with the long hot, dry season for about 8 months with dominant wind directions from the north and the east. This dry season is followed by a short rainy season of 3–4 months (June, July, August, and September) with the dominant wind directions from the south and the west. The mean monthly temperature ranges from 22.7 to 34.5°C. Average annual precipitation ranges from 147 mm at Khartoum to 454 mm at Sennar. Average monthly relative humidity ranges from 19% in the hot dry season to 70% in a rainy season. The mean annual evaporation rate ranges from 168 mm at Wad Madani to 215 mm at Khartoum [19]. According to available data from the NASA POWER (NASA Prediction of Worldwide Energy Resource), the mean daily relative humidity for the period from 1983 to 2000 was taken. Also, the mean monthly temperature and mean annual precipitation of the period from 1951 to 2001 were taken according to Abdel-Hameed [33] as shown in Table 1.

Table 1 The average annual climatic data of some meteorological stations in the Gezira area [33, 34]

No.	Meteorological station	Precipitation (mm/year) (1951–2001)	Temperature (°C) (1951–2001)	Relative humidity (%) (1983–2000)
1	Khartoum	149.55	29.44	38.12
2	Wad Madani	322.64	28.50	44.30
3	Sennar	455.92	28.42	47.11
4	Kosti	368.91	28.35	43.83
5	Ed Dueim	240.53	29.21	40.42

3.1 *Precipitation*

The mean annual precipitation for the period (1951–2001) for the Gezira area ranges from 456 to 150 mm at Sennar and Khartoum, respectively. The highest rainy months are July, August, and September in most of the Gezira area and also June in Kosti, Sennar, and Wad Madani. Also, the maximum amount of precipitation occurs in August (see Fig. 3). The average annual precipitation decreases northward from about 450 mm at Sennar to about 140 mm at Khartoum (see Fig. 4).

3.2 *Temperature*

The mean maximum daily temperature varies between 31 and 46°C. The mean minimum temperature varies from 15 to 27°C. The mean monthly temperature varies between 22.7 and 34.5°C. The mean temperature relatively increases northward at Khartoum, which changes from semiarid to arid zones.

3.3 *Relative Humidity*

The mean annual relative humidity differs from 19% at Ed Dueim to 71% at Sennar and Kosti. It is relatively high in the rainy season and low in hot months. It decreases northward.

4 Geological Setting

The geology of the Gezira area is a part of central Sudan geology (Gezira region), which is mainly occupied by Cretaceous, Tertiary, and Quaternary sediments. There are some basement outcrops on the southwestern part of the study area.

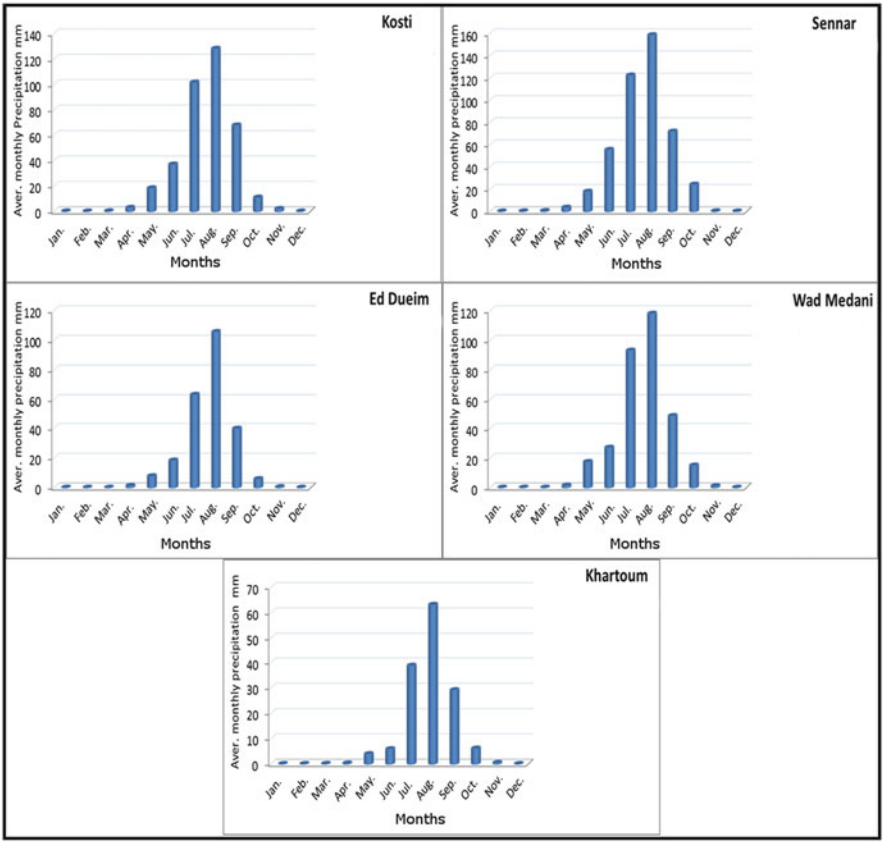


Fig. 3 Mean monthly precipitation in the Gezira area for 1951–2001

The basement rocks are of Precambrian age, which represents the oldest rocks in Gezira area. The area under investigation lies in the Blue Nile rift basin, which is traced by many faults [35]. The geologic units in the study area, from oldest to youngest, are described as the following:

4.1 Basement Complex

Whiteman [35] mentioned that Sudan had been occupied by basement complex with an area of about 50%. It consists of metasediments, quartzites, marbles, graphitic slates, pelitic schists, and gneisses. Intrusive rocks are porphyritic, felsite dykes and quartz diorites, which occur above the plain of the Gezira.

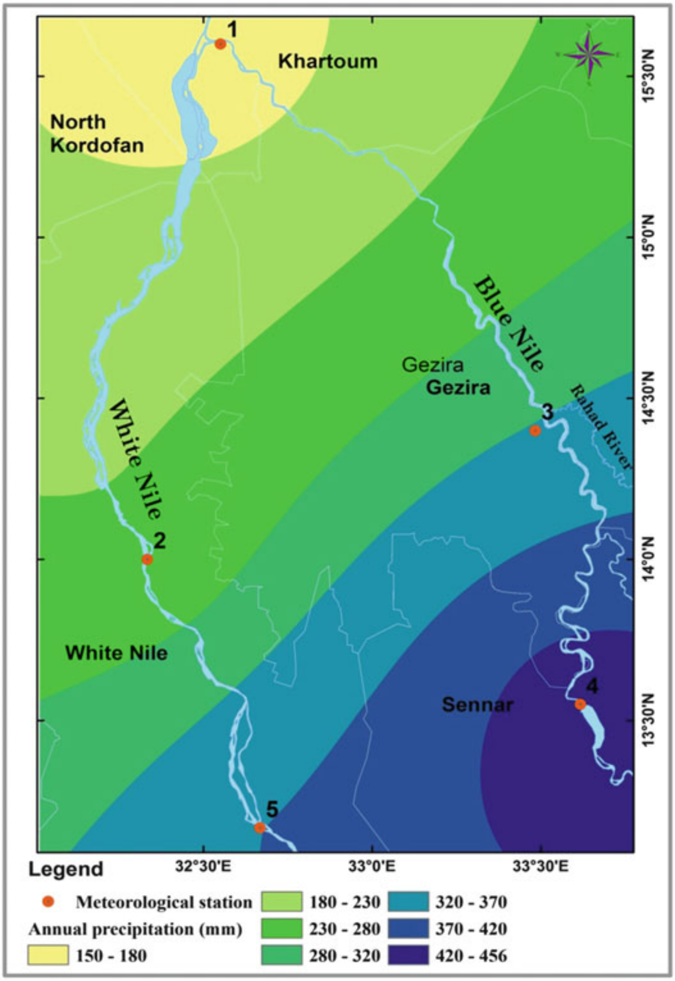


Fig. 4 Mean annual precipitation in the Gezira area for 1951–2001

4.2 Nubian Sandstone Formation

The Nubian Formation is probably of Mesozoic age. It is continental in origin due to some evidence such as plant fossils, a variation of lithology, and the presence of conglomerate bed at the base of formation [35, 36]. The Nubian Sandstone was redefined as those beds of conglomerates, grits, sandstone, sandy mudstones, and mudstone that overlay unconformably the basement rocks and Paleozoic Sandstone Formation [35]. The thickness of Nubian Sandstone Formation has reached about 305 m south and southwest around Khartoum. It differs from an area to another in the Gezira, where it reached to 73 m thick at Jebel Aulia, 244 m at Soba north of

Gezira area, and more than 113 m thick at wad El Turabi north Elhasahesa [10]. Whiteman [37] described the Nubian Sandstone Formation as pebble conglomerates, intraformational conglomerates, Merkhiyat sandstones, quartzose sandstones, and mudstones.

4.3 Gezira Formation

Gezira Formation is widely exposed in the Gezira area (see Fig. 5). It is unconformably overlying the Nubian Formation [19]. Based on Abdel Salam [10], the Gezira Formation is unconsolidated sediments and consists of clays, silts, sands, and gravels. At Ghubshan area, the base of this Formation consists of coarse gravelly sand with a 9 m thickness, which is overlained by clayey sand with a 35 m thickness. The Gezira Formation at its upper part consists of 17 m of dark clay that is known locally as Gezira clays [10].

According to Abdel Salam [10], there are three subdivisions that can be recognized within the Gezira Formation: Mungata member, lower sandy member, and upper clay member. Awad [38] recognized a basal member called Wad Madani member.

4.4 Recent Superficial Deposits

The Gezira Formation is covered by youngest deposits of the Pleistocene age and still depositing today. These deposits are represented by the wind-blown sand (Qoz deposits) and wadi and Khor deposits. The Qoz deposits are fixed dunes that are found in scattered areas in Gezira, along with the banks of the White Nile and around El Hasaheisa. At the areas around El Manaqil, these deposits are unconformably overlying the Nubian Formation. They lie within the basin of the Blue Nile, which is a part of the major graben fault system that forms the Blue Nile basin. This graben is one of the three significant grabens, which is formed as a result of Blue Nile rift taking the NW-SE direction that is extending from Sabaloka to the border of Ethiopia.

5 Hydrology and Hydrogeology

5.1 Surface Water

The main rivers bounding the Gezira are the Blue Nile to the east and White Nile to the west. The Blue Nile feeds the irrigation projects in the Gezira area and the Gezira scheme. There are two main canals draining from the Sennar reservoir with a

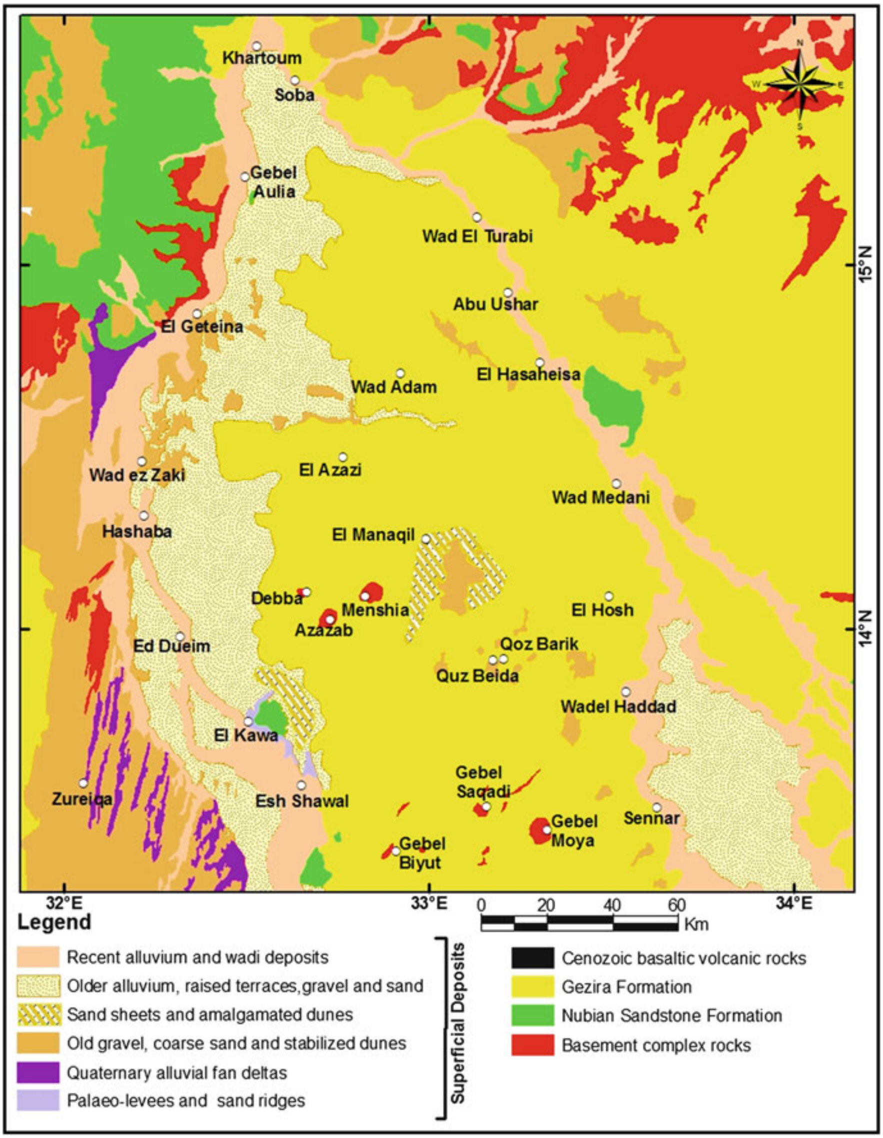


Fig. 5 Geological map of central Sudan (Geological Research Authority of Sudan 1988)

capacity of 3.54 m^3/s for about 2,300 km of branches and major canal network. Moreover, these canals are supplying around 1,500 minor irrigation canals with a total length of 8,000 km. The Gezira scheme is not an advanced one by the present day principles. This irrigation system was designed based on the flat topography of the Gezira (gravity irrigation system), which is adopted as a tenancy system [39].

5.2 Groundwater Occurrence

The groundwater in the Gezira area occurs in two principal aquifers: the Gezira Formation (Quaternary aquifer) and the Nubian Sandstone Formation (Cretaceous aquifer). The outcrops of basement rocks represent the local recharge area for the water in El Manaqil and south Gezira areas. The Cretaceous aquifer has been studied for performing the present work, with a general description of the Quaternary aquifer and the basement rocks.

5.2.1 Basement Rocks

Fractured aquifers are not recorded in the study area. The basement complex is the oldest exposed rocks in the Gezira. The outcrop areas of these rocks are small and produce little water due to the impervious Gezira clay, which hamper its replenishment. There are no boreholes producing from this formation, except a few hand-dug wells. These wells are supplying saline water [35].

5.2.2 Nubian Sandstone Formation (NSF)

The Nubian Sandstone Formation (NSF) is the most important water-bearing formation in Sudan and the second in importance after the Gezira Formation in central Sudan at Gezira area [10, 35]. It is overlained by Gezira Formation and underlained by the basement complex with unconformity surfaces. The thickness of a mudstone is moderately great, and in the northern Gezira, it is more than that in the south- central Gezira, mainly at El Manaqil. This thickness variation is caused by the erosion processes and sedimentation, consequently creating thick beds of intraformational conglomerates [40]. Elzein [25] constructed geologic cross sections based on the combination of geologic and geoelectrical correlations along some lines through Gezira area. The Nubian aquifer composed of sandstone, gravelly sandstone, and intercalation from mudstone and limestone. It is a confined aquifer covered by Gezira Formation except at the areas around El Manaqil area. The water-bearing layers in the Gezira contain mostly sandstones and conglomerates [10, 35]. The thickness of the NSF in the areas south and southwest of El Manaqil ranges between 0 and 40 m caused by the shallow depths of basement rocks [25].

5.2.3 Gezira Formation

The Gezira Formation is the main aquifer in the Gezira area. It has sufficient potential amount of good groundwater quality used for different purposes [10, 25]. Furthermore, in the areas where Gezira Formation is thin, the Nubian aquifer is the main aquifer in these areas. The Gezira Formation unconformably overlies the Nubian Sandstone Formation. Elzein [25] mentioned that it is difficult to detect the accurate distinction between Gezira and Nubian Sandstone Formations, especially from the data of borehole. Due to rapid changes in the thickness and facies of the Gezira Formation. The Gezira Formation consists of clay, sand, gravel and kankar nodules [10, 25]. The correlation of the Gezira deposits along vast distance is difficult, due to these deposits are lens shaped and interfingering bodies. Moreover, quick changes in the facies and pinch out of these bodies were recorded [25].

The Gezira aquifer is covered in most areas by Gezira clay. The water-bearing beds are tortuous interconnected sand forms which are occurring under this impermeable clay cover [10, 35]. The coarse gravelly sand horizon is considered the best water-producing one. The thickness of Gezira Formation varies from less than 10 m southwest of the study area around El Manaqil and Dar Nail to more than 100 m south Abdelaziz. Around the areas of Elremeitab and Sherif Elhendi at the southeast of the study area, the thickness ranges from 50 to less than 80 m. At the center of the study area, it ranges from 30 to 50 m [10].

6 Piezometric Characteristics of the Aquifer System

The main factors controlling the depth to water from ground surface are the topography, geological setting, and the distance from the Blue Nile. The measured elevations of the piezometric levels for the selected wells during the field study are shown in Table 2. The piezometric levels are controlled by the topography and differ from 369.4 to 406.6 m above sea level (masl) (see Fig. 6). The main groundwater flows in two directions: east-west and southwest direction. The water levels near the Blue Nile at the east of the study area are higher than those in the southwest around Dar Nail.

7 Physicochemical Parameters of Groundwater

*7.1 Temperature (*T*)*

The increase of water temperature may affect the concentration of elements, increase the reaction in water, and increase the growth of microorganisms, which may severe the taste, odor, color, and corrosion problems [41, 42]. The temperature rises about 2.9°C every 100 m depth [43]. The maximum temperature was recorded at well No. 31, El Foqraa, as 35.2°C, whereas the minimum one was 28.5°C at well No. 21, East Nuweila, and the average temperature is 32°C (see Fig. 7). These variations in groundwater temperature are usually related to changes in water depths.

Table 2 Piezometric water levels of the Nubian Sandstone Aquifer and the Gezira aquifer

Well no.	Well name and location	Formation	Total depth (m)	Water level (masl)
1	Wad Madani	Nubian Sandstone	85	394.7
2	Center of Elsook	Nubian Sandstone	158.5	399.3
3	Um Sunut	Nubian Sandstone	110	397.5
4	Sherif Elhendi	Nubian Sandstone	92.4	406.6
5	Hillat Romeitab	Nubian Sandstone	141.8	392.4
6	El Manaqil square 35	Nubian Sandstone	127.7	380.8
7	South Dar Nail	Nubian Sandstone	92	377.4
8	East Um Talha	Nubian Sandstone	97	369.4
9	Center of Elhomira	Nubian Sandstone	213	374.1
10	El Hasaheisa	Nubian Sandstone	128.7	388.4
11	West Um Seyala	Nubian Sandstone	–	390.6
12	Osman Ferah	Nubian Sandstone	84.4	382.2
13	Um Duana Alahamda	Nubian Sandstone	92	377.9
14	Gezoly Abo Reesh	Nubian Sandstone	95	382.1
15	Um Gulud	Gezira	64.8	385.3
16	Um Ood	Nubian Sandstone	70	387.3
17	Almosallamia	Nubian Sandstone	112	389.5
18	Elmadina arab	Nubian Sandstone	87.5	389.2
19	wad Elgamal	Nubian Sandstone	95	386.0
20	wad Matar	Nubian Sandstone	92.4	389.7
21	East Nuweila	Nubian Sandstone	92	383.2
22	Wad Elgaleb	Nubian Sandstone	121.5	378.2
23	El Radma	Nubian Sandstone	94.2	382.6
24	Bika	Nubian Sandstone	93	391.4
25	wad Elameen	Nubian Sandstone	213.4	379.5
26	Hag Idrees	Nubian Sandstone	80.9	389.7
27	Tibat	Gezira	–	394.7
28	Abdelaziz	Nubian Sandstone	96	390.6
29	Wad Elshafi	Nubian Sandstone	122.7	392.5
30	Nail Village	Nubian Sandstone	90	392.6
31	El Foqraa	Nubian Sandstone	110.6	396.8

7.2 pH Value

The pH is a very sensitive parameter, and the reactions can occur immediately after sampling that will change the pH, so it must be measured in situ. According to the WHO [44], a range of the pH of 6.5–8.5 is allowable for drinking water (see Fig. 7).

The pH values of the Nubian aquifer range from 6.8 in well No. 25 in Wad Elameen to 7.7 in well No. 5 in Hillat Romeitab with an average value of 7.2. The pH of the two surface water samples is 8. Therefore, all the pH values of water samples are in the acceptable range. In general, the pH values decrease away from the Blue Nile; this may be because of the negligible recharge from the Blue Nile.

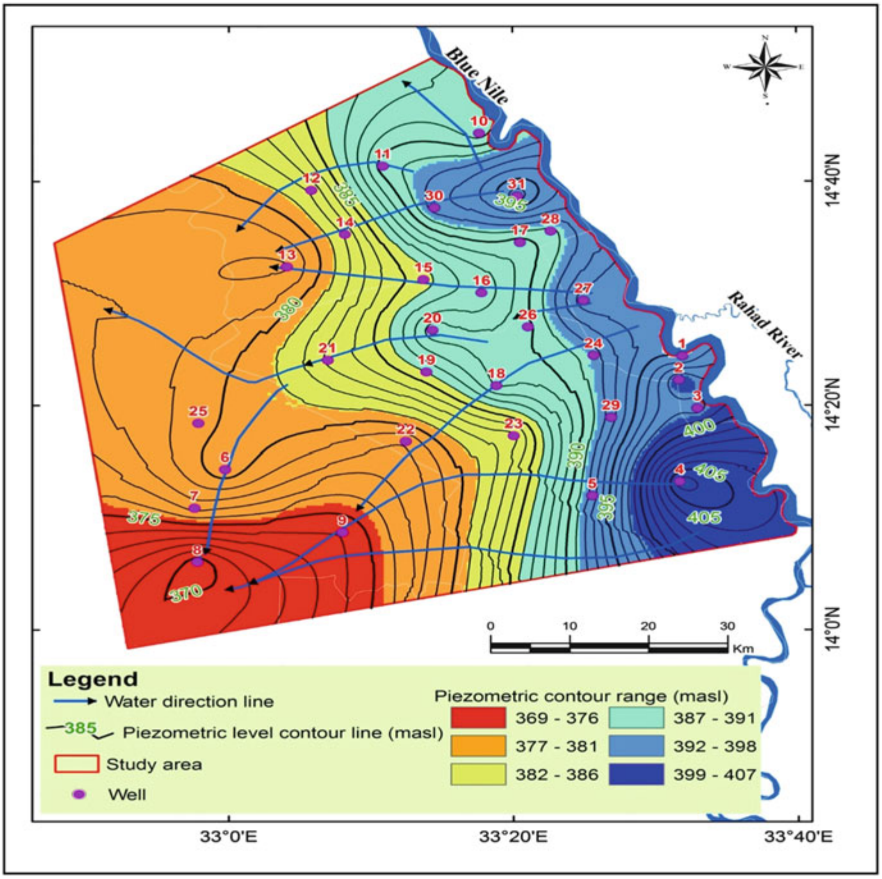


Fig. 6 The spatial distribution of piezometric levels in the Gezira and Nubian Sandstone Aquifers with groundwater flow directions in 2013

7.3 *Total Dissolved Solids (TDS)*

Total dissolved solids (TDS) are considered as an essential factor in the determination of water types and its suitability for different purposes. In the present chapter, the TDS values of the Nubian aquifer are ranging from 263 ppm in well No. 31 in El Foqraa to 1,070 ppm in well No. 25 in Wad Elameen with an average value of 500 ppm. It is observed that the higher values of TDS are in the west and southwest of the study area (i.e., Wad Elameen and El Manaqil vicinity), which may be due to the leaching processes caused by the movement of water from east to west. The lowest TDS values were at the wells near or close to the Blue Nile (see Fig. 7).

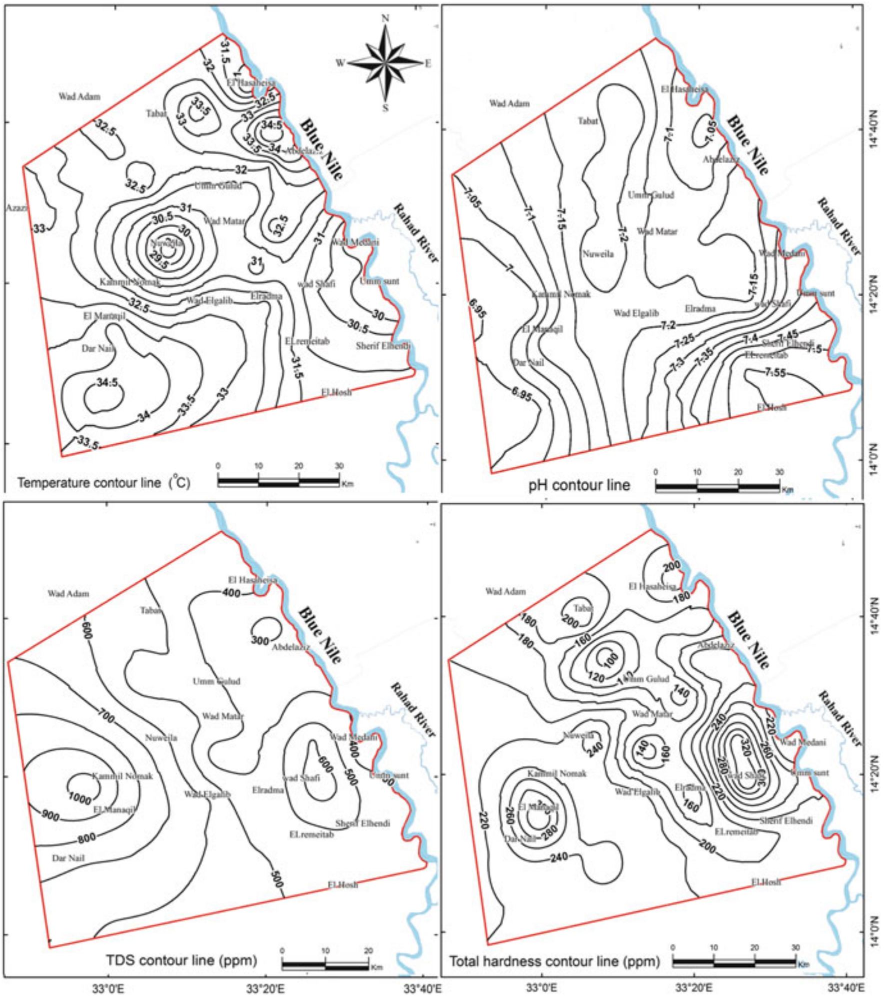


Fig. 7 Physicochemical characteristics of the Nubian Sandstone groundwater

7.4 Total Hardness

The total hardness as due to $CaCO_3$ varies from 82 ppm in well No.14 in Gezoly Aboreesh to 345 ppm in well No. 29 in Wad Elshafi with an average of about 207 ppm. The total hardness of the surface water samples varies from 50 to 70 ppm for the White and Blue Niles, respectively.

According to the hardness classification of Sawyer and McCarthy [45], all surface and groundwater samples are less than the tough class, except the groundwater samples Nos. 6, 24, and 29. The higher hardness values are in the areas of Wad Elshafi and El Manaqil vicinities (see Fig. 7), which may be due to the leaching and dissolution of carbonate salts rich in Ca^{2+} and Mg^{2+} ions within the water-bearing sediments.

7.5 Major Cations

7.5.1 Calcium (Ca^{2+})

Calcium concentrations of Nubian aquifer samples varied from 17.95 ppm in well No. 14 Gezoly Aboreesh to 80 ppm in well No. 6 El Manaqil square 35 with an average value of 50.9 ppm. Its concentration in Blue and White Niles samples are 20 ppm and 16 ppm, respectively. According to the spatial distribution of calcium, it increases away from the Blue Nile at El Manaqil vicinity areas (see Fig. 8). This increase is due to the movement of groundwater, which caused an increase in dissolution of calcium carbonates and gypsum minerals and the increase in distance from recharge area. Elzein [25] confirmed that the calcium values increase toward the central Gezira, which are caused by the dissolved calcium with depth and distance from recharge area.

7.5.2 Magnesium (Mg^{2+})

Sodium and calcium ions are larger than magnesium ions, and magnesium ion is one of the essential elements for the animals and plants [46]. According to the results of the present work, the concentration of magnesium ranges from 9.04 ppm in well No. 14 Gezoly Aboreesh to 39.86 ppm in well No. 29 Wad Elshafi with an average value of 19.47 ppm. Figure 8 shows the spatial distribution of magnesium ions, which reflect high values in the southwest and west-southwest of the study area. Concerning surface water, magnesium concentration in Blue and White Niles samples is 4.88 and 3.66 ppm, respectively.

7.5.3 Sodium (Na^{+})

The concentration of sodium in water can be affected by anthropogenic activities. The concentration of sodium in water samples representing the Nubian aquifer varies from 6.7 ppm in well No. 3 (Um Sunut) to 208.7 ppm in well No. 25 (Wad Elameen) with an average value of 60.35 ppm. The sodium content in surface water is 18.86 ppm and 9.89 ppm for the Blue and White Niles, respectively. The highest value of sodium concentration was recorded at the west of the study area at Kammil Nomak and El Manaqil areas, while the lowest values were recorded in the areas close to the Blue Nile (see Fig. 8).

These high values may be due to the leaching processes of sodium-rich sediments as a result of groundwater flow from the east to the west at El Manaqil.

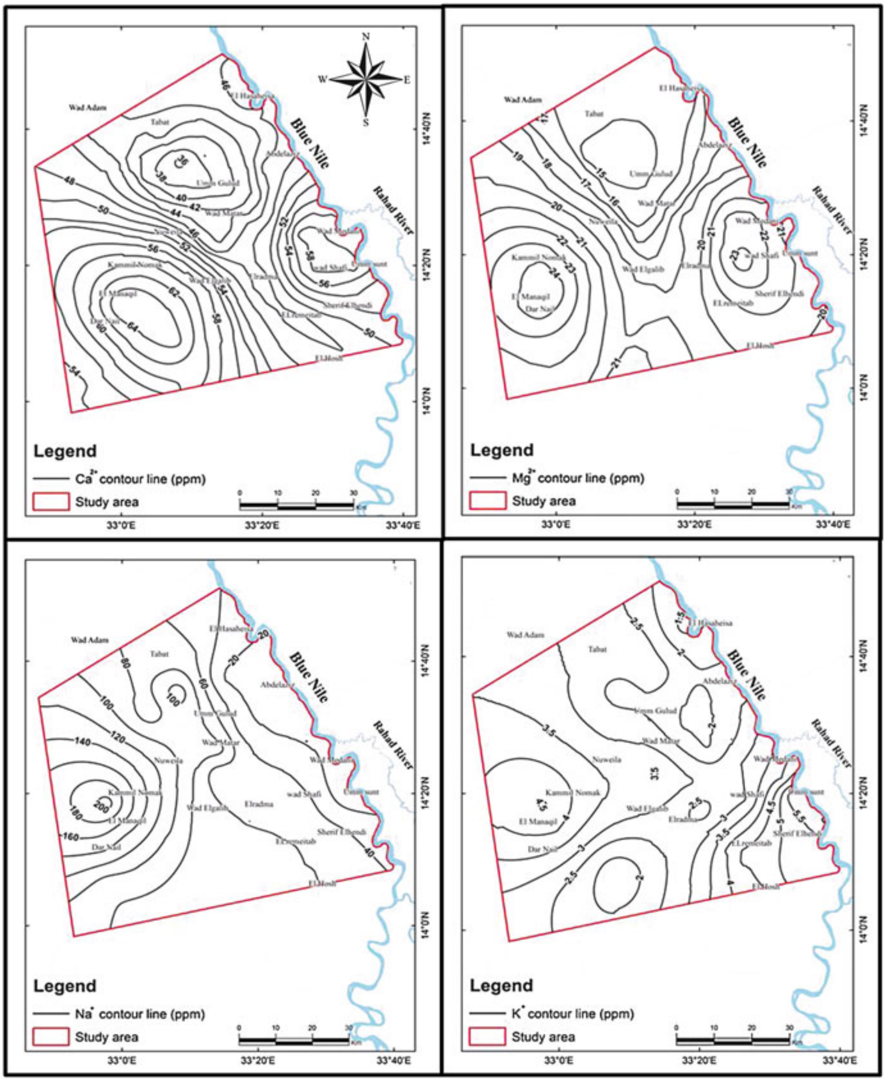


Fig. 8 Distribution of major cations in the Nubian Sandstone groundwater

Salama [47] concluded that the buried saline lakes in Gezira were affected by the continuous evaporation process. The precipitation washed the residual deposits of NaCl and Na_2SO_4 to the deepest parts at the central Gezira.

7.5.4 Potassium (K^+)

The potassium values in the study area range from 1.28 ppm in well No. 10 in El Hasaheisa to 5.87 ppm in well No. 3 in Um Sunut with an average value of

3.05 ppm. Spatial distribution of potassium shows the increase values toward southeast and west of the study area (see Fig. 8). The potassium values of surface water are 9.78 ppm and 2.74 ppm for Blue and White Nile, respectively.

7.6 Major Anions

7.6.1 Chloride (Cl^-)

Chloride concentration varies from 185.3 ppm in well No. 25 to 2.15 ppm in well No. 4 with an average value of 39.27 ppm. Its concentrations in Blue and White Niles samples are 46.15 ppm and 17.75 ppm, respectively. The acceptable limit of chloride in drinking water is 250 mg/L [44]. The spatial distribution of chloride in Nubian aquifer shows the lowest values in the areas close to the Blue Nile and increases to the west (see Fig. 9).

7.6.2 Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^-)

Carbonate ions are represented in all water samples of Nubian aquifer except samples Nos. 1 and 2. Also, it is absent in surface water samples. The maximum carbonate value is 60 ppm in well No. 5 in Hillat Romeitab with an average concentration of about 20.5 ppm. The spatial distribution of carbonate ions is increasing toward the center and southeast of the study area. The concentration of bicarbonate ranges from 151.35 ppm in well No. 19 in Wad Elgamal to 402 ppm in well No. 25 in Wad Elameen with an average value of 252 ppm. The concentration is increasing westward at the Wad Elgalib vicinity (see Fig. 9). The concentrations in the Blue and White Niles are 30.5 ppm and 36.6 ppm, respectively.

7.6.3 Sulfate (SO_4^{2-})

Sulfates are mainly resulting from sedimentary rocks, mainly anhydrite and gypsum. The sulfate concentration varies from 185 ppm in well No. 24 (Bika well) to 2.9 ppm in well No. 3 (Um Sunut well) with an average value of 53.5 ppm. The highest values are in the areas at wad Shafi, west Wad Madani, west El Manaqil, and Kammil Nomak, but the lowest concentrations occur at Abdelaziz area (see Fig. 9). The values of the analyzed surface water samples are 32.16 ppm and 24 ppm for the Blue and White Niles, respectively.

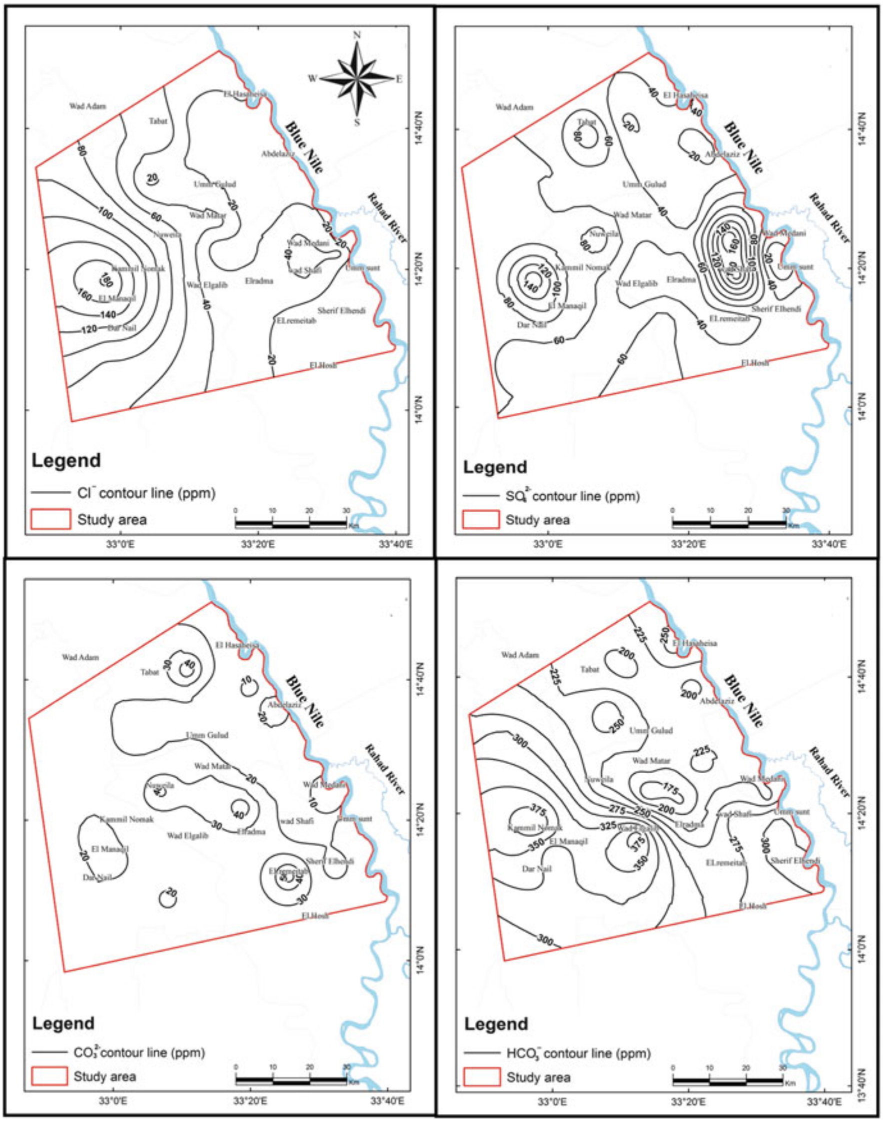


Fig. 9 Distribution of major anions in the Nubian Sandstone groundwater

7.6.4 Nitrate (NO_3^-)

Nitrate is considered as one of the most common groundwater contaminants in the world, and its occurrence in higher levels threatens human health and constitutes ecological hazards [48]. The maximum desirable limit of nitrate concentration for drinking water is 50 mg/L as NO_3 [44]. The concentration of nitrate in the

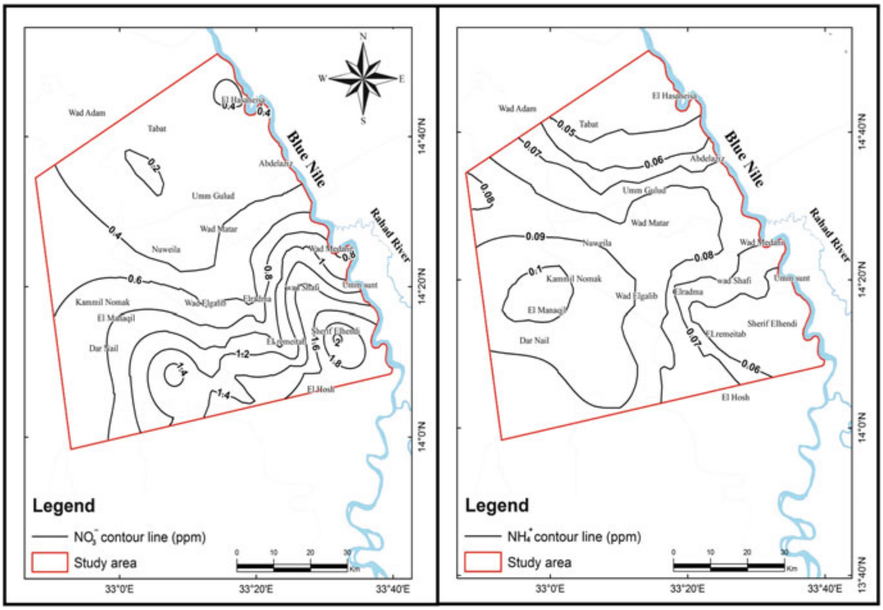


Fig. 10 Distribution of NO_3^- and NH_4^+ in the Nubian Sandstone groundwater

groundwater varies from 0.09 ppm in well No. 28 in Abdelaziz to 4 ppm in well No. 4 in Sherif Elhendi with an average value of 0.7 ppm. The concentration increases southward and southeastward of the study area (see Fig. 10). The high concentrations may be as a result of increased anthropogenic activities in these areas.

7.7 Ammonium (NH_4^+)

The typical natural levels of ammonium in ground and surface waters are generally below 0.2 mg/L [49]. The high levels of ammonium in ground and surface waters originate from agricultural, industrial, sewage, bacterial, and animal waste pollution. In the study area, the ammonium concentration in Nubian aquifers ranges from 0 ppm in well No. 3 in Um Sunut to 0.19 ppm in well No. 25 in Wad Elameen with an average value of 0.07 ppm. The ammonium increases from areas close to the Blue Nile to the west of the study area at Kammil Nomak vicinity areas (see Fig. 10). The toxic effect is noticed only at levels over about 200 mg/kg of body weight [49].

7.8 *Heavy Metals*

In general, there are no any noticeable pollution traces, except wells Nos. 8 and 12, which show a slight rising in iron (see Fig. 11). The permissible limit is 1 ppm [50]. The high levels of iron in those two wells may be attributed to the leaching processes of iron oxides in the Nubian Formation [25].

7.9 *Suitability of Groundwater for Different Purposes*

Groundwater in the study area is mainly used for drinking, domestic, and agricultural purposes. According to the international standards for drinking water [44], the groundwater quality of the Nubian aquifer in the study area is fit for drinking and domestic uses except well No. 25, which is occurred on the western side of the study area. It shows a slight increase in total dissolved solids and sodium concentration.

7.9.1 Suitability for Drinking and Domestic Use

Water for drinking and domestic purposes must be safe and clear from any harmful constituents. According to the international standards for drinking water [44], the groundwater quality of the Nubian aquifer in the study area is fit for drinking and domestic uses except well No. 25, which is occurred on the western side of the study area. It shows a slight increase in total dissolved solids and sodium concentration.

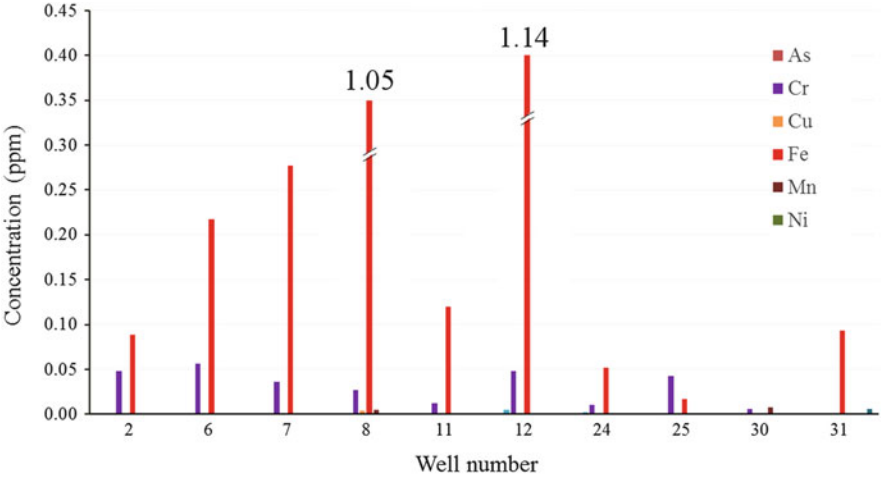


Fig. 11 Concentration of heavy metals in the Nubian Sandstone groundwater

Moreover, the water quality of Nubian aquifer is excellent and suitable for livestock consumption according to the guidelines of National Research Council [51].

7.9.2 Suitability for Irrigation Purposes

Assessment of groundwater of the Nubian aquifer in the study area is very important to stand on its suitability for irrigation uses. The water quality that is used in irrigation is considered as an important factor to protect the soil from degradation, quality, and productivity of irrigated crops. Some factors control the suitability of water for irrigation purposes: sodium adsorption ratio (SAR) and soluble sodium percentage (SSP).

7.10 Sodium Adsorption Ratio (SAR)

Sodium adsorption ratio (SAR) is considered as one of the most important parameters to measure the suitability of water for irrigation use because the concentration of sodium can reduce the soil structure and soil permeability [52]. Moreover, it is responsible for the sodium hazards for crops. It is computed by the following equation given by [53] as:

$$\mathrm{SAR} = [\mathrm{Na}]/\mathrm{SQRT}\ \{([\mathrm{Ca}] + [\mathrm{Mg}])/2\}$$

where, sodium, calcium, and magnesium concentrations are expressed in meq/L. Figure 12 illustrates the SAR values plotted against the EC values on the US salinity diagram to classify the water samples according to their irrigational uses. The groundwater samples from the Nubian aquifer in the study area are considered moderately suitable for irrigation purposes.

7.11 Soluble Sodium Percentage (SSP)

Sodium content in water is expressed in terms of soluble sodium percentage or sodium percentage defined by the following equation [54]:

$$\mathrm{SSP} = \mathrm{Na} \times 100/(\mathrm{Ca} + \mathrm{Mg} + \mathrm{Na})$$

where the concentrations of all ions have been expressed in meq/L.

Wilcox diagram shows the correlating sodium percent against the electrical conductivity (μS/cm), which indicates that 69% of the total 29 well water samples fall in the excellent to good category and 24% fall in good to permissible limit (see Fig. 13). Finally, only 7% of the samples (14, 25) fall in the permissible to the

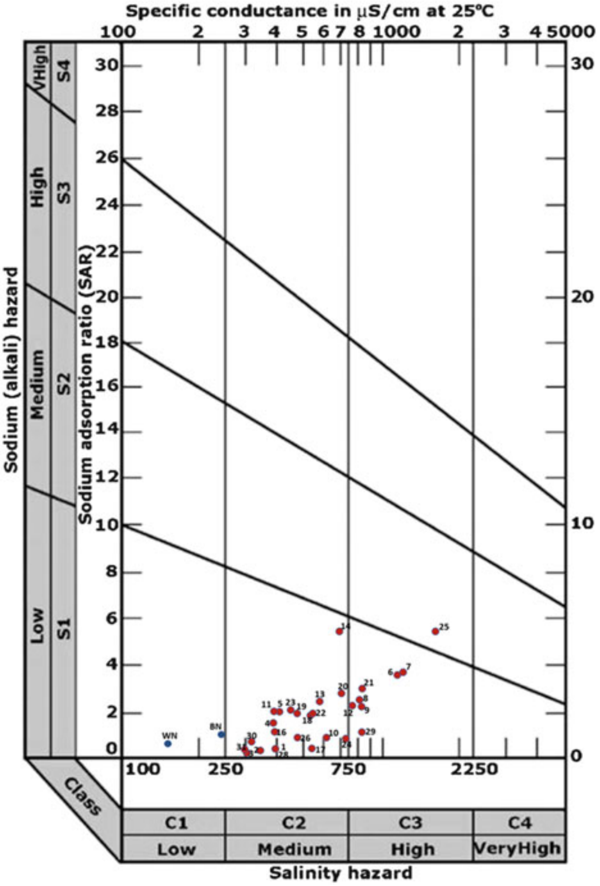


Fig. 12 Surface and groundwater samples plotted on the US salinity diagram for classification of irrigation water [53]

doubtful limit, which reflects the suitability of all samples for irrigation. Surface water samples fall in the excellent to the good limit.

8 Impact of Land Use/Land Cover Changes on the Water Quality

Remote sensing is a handy tool for the monitoring of the environment and global climate understanding and monitoring and detection of land cover and vegetation changes. Land cover and vegetation recognition in the Gezira area were applied by computing the NDVI and the maximum likelihood method of supervised classification. For this purpose, satellite images of different remote sensors were used

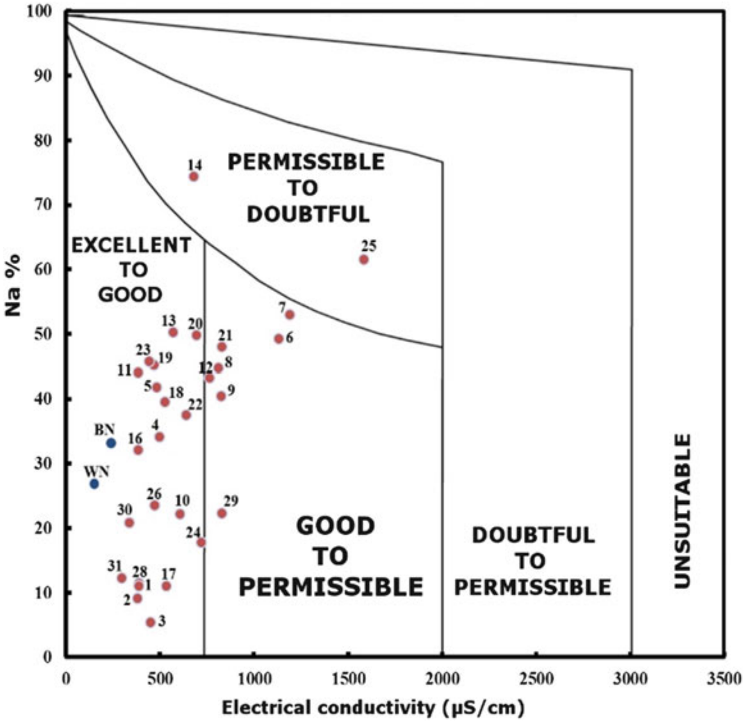
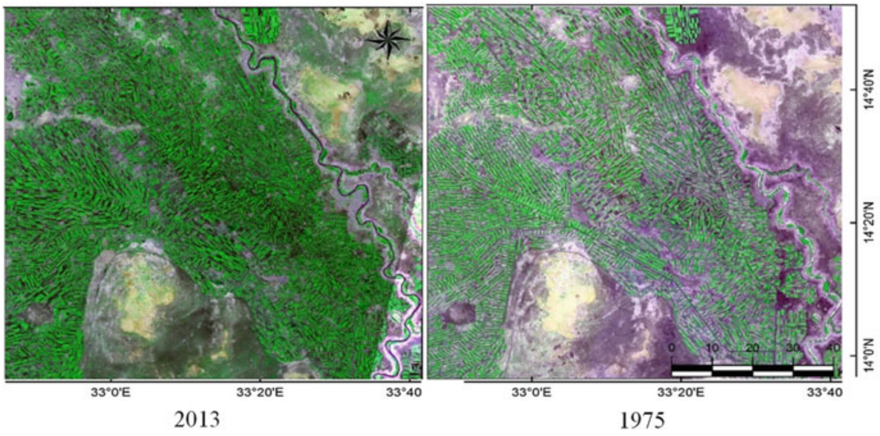


Fig. 13 Suitability of water samples for irrigation uses on Wilcox diagram



2013 1975

Fig. 14 Color composite (RGB 241) Landsat 2 MSS image (1975) and (RGB 453) Landsat 8 OLI image (2013) for the Gezira area

(Landsat MSS, OLI) to produce land cover and vegetation maps. In the satellite images, the ENVI 4.8 and ArcGIS 10.3 software were used. The study area was buffered with a distance of about 3 km. Figure 14 shows the Landsat 2 MSS and

8 OLI images for the study area of years 1975 and 2013, respectively. Before the classification and image processing, the following processes were conducted [55, 56]:

1. The images were georeferenced and geographically converted from WGS84 (UTM-Zone 36 datum) to WGS84-World Mercator coordinate system and resampled to a standard 25 m resolution.
2. Radiometric calibration for conversion of the radiance values to reflectance.

8.1 Normalized Difference Vegetation Index (NDVI)

Calculations of NDVI for a given pixel always result in a number that ranges from minus one (−1) to plus one (+1); however, no green leaves gives a value close to zero. A zero means no vegetation and close to +1 (0.8–0.9) which indicates the highest possible density of green leaves [57].

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$$

For the Landsat 2 MSS sensor, the NIR is band 7 of the wavelength range (0.8–1.1 μm), and the red is band 5 (0.6–0.7 μm). The NIR and red bands of Landsat 8 OLI are band 5 of wavelength range (0.85–0.88 μm) and band 4 of wavelength (0.64–0.67 μm), respectively. The NDVI map of 1975 shows values varying from −0.97 to almost 0.52 (see Table 3), while the mean NDVI value of the whole catchment is −0.2. The spatial distribution of the vegetation is characterized by relative dense, growing vegetation in regions west of the Blue Nile compared to the areas south of Gezira and east of the Blue Nile where bare land increased. The NDVI map of 2013 represents values ranging from −0.39 to 0.64 (see Table 3). It is clear that the vegetation of 2013 is denser in vegetation compared to the year 1975, mainly in regions that are dominated by agricultural land. This fact can also be determined by the frequency distribution of NDVI values of each year (see Fig. 15).

8.2 Land Use/Land Cover (LU/LC) Classification

Land use/land cover classification was accomplished using the maximum likelihood algorithm [58] depending on the signatures of training regions. Landsat

Table 3 Simple statistical description of NDVI values in years 1975 and 2013

	Year	
	1975	2013
Minimum	−0.97	−0.39
Maximum	0.52	0.64
Mean	−0.2	0.13
Standard deviation	0.13	0.09

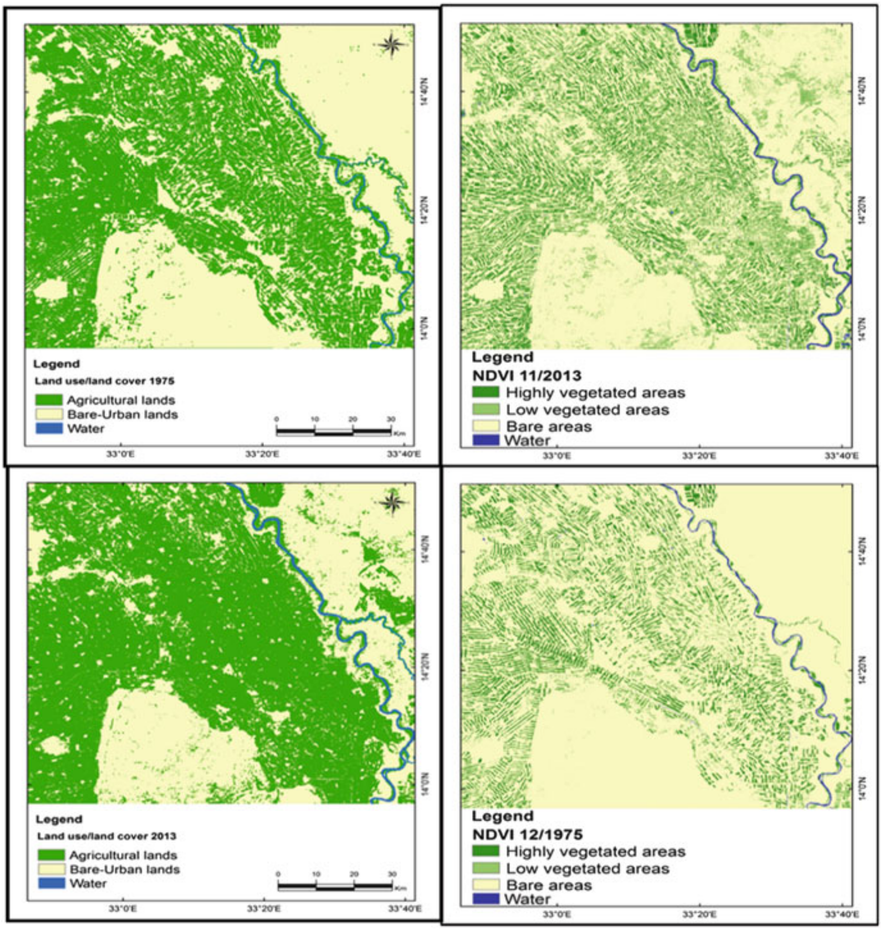


Fig. 15 Land use/land cover categories and NDVI of the study area and the neighborhood areas for the years 1975 and 2013

8 (November 2013) was classified firstly as a recent image and compared with the Google Earth and with that of unsupervised classification (K-means algorithm) [59] to create a highly accurate classification.

The SAM supervised algorithm was used to classify the Landsat 2 (December 1975) and compared with the unsupervised algorithm for the same image. The results of classified categories included agricultural land, bare-urban land, and water (see Fig. 15).

Table 4 represents the results of LU/LC for the period (1975–2013), which indicates the increase of agricultural activities and water bodies. The bare and urban lands were decreased (see Fig. 15).

Table 4 Land use/land cover classification in the study area and vicinity for the time (1975–2013) and the associated variations

Land use/land cover (LU/LC)	Year 1975		Year 2013		Change % 1975–2013
	Area (km^2)	(%)	Area (km^2)	(%)	
Agricultural land	5,708	51.73	6,602.97	59.50	7.78
Bare-urban land	5,287	47.91	4,431.43	39.94	−7.98
Water	40	0.36	62.14	0.56	0.20
Total	11,035	100	11,096.55	100	

According to the results both of hydrochemistry of the Nubian aquifer and land use/land cover changes, there is no any hazards from the increased agricultural activities on the water quality of Nubian aquifer in the study area. This is as a result of the presence of a thick clay layer that capped the aquifer of Gezira which protected the aquifer systems from any pollution sources which may reach to the Nubian aquifer.

9 Stable Isotopes of δ^2H and δ^{18}O

The ratios of stable isotopes of water (δ^{18}O, δD or δ^2H) are among the most essential tools for defining the hydrogeological processes in natural systems [60]. Moreover, deuterium and oxygen 18 are considered the perfect water geochemical tracers. This is because their concentration is not affected by interactions with the water-bearing materials. The most important natural processes which cause variations in the contents of isotopes of waters are evaporation and condensation. So, extensive evaporation leads to lower deuterium and oxygen 18 contents in water vapor than the water body. Consequently, the water with high content of heavy isotopes as a consequence of evaporation can be identified their contribution to the groundwater. Many researchers studied the interrelation between the surface and groundwater in central Sudan, among them [61–65].

All data of δ^2H and δ^{18}O data of surface water and rainfall samples were taken from the published and unpublished works. Rainfall data was taken based on [62]. White Nile data has been taken according to ([61, 65]). Finally, Blue Nile data were taken according to [63–65]. Some of these data are of specific locations. Others are located in the central Sudan without any information about their definite location (see Table 5).

Analyzed data of Nubian aquifer for samples Nos. 2, 6, 7, 8, 12, 14, 18, 20, 21, 22, 24, and 25 were carried out for determination of stable isotopes, deuterium (δ^2H), and oxygen 18 (δ18O) in per mil (‰) (see Table 6).

The values of δ^{18}O and δ^2H for groundwater sample No. 2 are −6.06 and −5.53‰, respectively. However, these values are not the same ratios for the δ^{18}O

Table 5 Data of δ^{2}H and δ^{18}O for rainfall and surface water (Blue and White Niles) used in the present study according to [61, 63–66]

Date/year	δ^{18}O (‰)	δ^{2}H (‰)	Deuterium excess
Rainfall			
1962	−2.12	−11	6.1
1963	0.21	8.9	7.3
1964	−2.64	−13.9	7.3
1965	2.56	14.4	−6.1
1966	−1.65	–	–
1973	2.92	25.3	2
1974	0.01	4.7	4.7
1975	−2.57	−14.5	6.1
1976	0.66	10.9	5.7
1977	−1.64	20.4	0.4
1978	−1.75	−10	−0.8
Nubian aquifer			
	−9.5	−68	
	−9.8	−70	
	−10.5	−77	
Blue Nile			
–	0.3	17	–
–	5.8	37	–
–	1.36	17.58	–
–	−0.1	11	–
White Nile			
10/2005 to 2/2006	2.1	19.7	–
10/2005 to 2/2006	3.3	21.4	–
10/2005 to 2/2006	3.1	17.5	–
–	0.9	11	–
–	1.9	16	–
–	4.4	35	–

and δ^{2}H for any of the water samples, as shown in (see Table 6). Moreover, the interpretation of this phenomenon is unknown for the author. Consequently, these values will be excluded from the results. The average annual value of δ^{18}O and δ^{2}H of rainfall according to the IAEA [66] ranges from −2.64 to 2.92‰ and −14.5 to 25.3‰, respectively (Table 5). The δ^{18}O and δ^{2}H data of paleowater of the Nubian aquifer in the northeast area of Khartoum were taken based on Haggaz and Kheirallah [64].

The isotopic composition of Blue Nile depends on Haggaz and Kheirallah [64] and [65], ranges from −0.1 to 5.8‰ and 11 to 37‰, respectively. Finally, the δ^{18}O and δ^{2}H of the White Nile have been taken based on Abdalla [61] and Vrbka et al. [65], illustrating a relatively similar range of the Blue Nile. They range from 0.9 to 4.4‰ and 11 to 35‰, respectively (see Table 5).

Table 6 Isotopic composition of the Nubian Sandstone Aquifer samples

Sample no.	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Distance from the Blue Nile (km)	Depth to water level (m)
2	−6.06	−5.53	3.2	19.5
6	−3.91	−20.23	68.4	42.1
7	−5.47	−35.2	70.6	37.8
8	−6.29	−41.82	76	46.39
12	−2.06	−6.19	29.7	24.7
14	−2.14	−6.62	30.7	24.6
18	−0.75	2.22	25.9	26.65
20	−5.36	−35.69	29.3	24.3
21	−2.99	−12.9	42.9	30.9
22	−3.11	−11.28	45.4	32.9
24	−1.53	−0.26	8.8	18.05
25	−3.15	−16.43	68.1	34

The isotopic composition results indicate that the 11 groundwater samples from the Nubian aquifer in the study area show a considerable variation of $\delta^{18}O$ and $\delta^{2}H$ concentration (see Table 6). These values lie in a wide range between −0.75 and −6.29‰ and 2.22 and −41.82‰, respectively. The plot of $\delta^{2}H$ against $\delta^{18}O$ (Fig. 16) was compared to the Global Meteoric Water Line (GMWL), which is described by $\delta^{2}H = 8\ \delta^{18}O + 10$.

The isotopic composition data of the Nubian aquifer in the study area can be distinguished into three groups (see Fig. 16). The first group is isotopically enriched, and it is represented by the samples Nos. 12, 14, 18, and 24. Moreover, these samples lie near the Blue Nile and in the areas near the center of the study area. This group forms a cluster around the GMWL, but it also plotted close to the Blue Nile samples. So, due to the isotope signature of this group and its location close to samples of the Blue Nile, it is considered as an indicator of recharge from the Blue Nile through the Gezira aquifer.

The second group is relatively depleted in isotopic composition compared to the Blue Nile and the first group samples. The water samples Nos. 6 and 25, which are located in the western part of the study area, are vigorously mixed with those of isotopically enriched samples. They are located away from the Blue Nile, and however, they are relatively enriched in isotopic composition compared to the third group, which are located in the perched groundwater bodies and are affected by the infiltration from the irrigation water. Also, their chloride values are high, which means may be affected by evaporation process than the vicinity samples.

The third group is more depleted compared to the Blue Nile samples. It is represented by samples Nos. 7, 8, and 20, which occupied the west (Nos. 7 and 8) and center (No. 20) parts of the study area. Sample No. 20 in the center of the study area may be not influenced by the groundwater flow paths and infiltration or percolation from irrigation canals or Gezira aquifer. Hence, it is depleted in isotopic composition compared to the neighborhood samples. The regression line equation for the groundwater samples in the study area is given as $\delta^{2}H = 8.4\ \delta^{18}O + 11.4$.

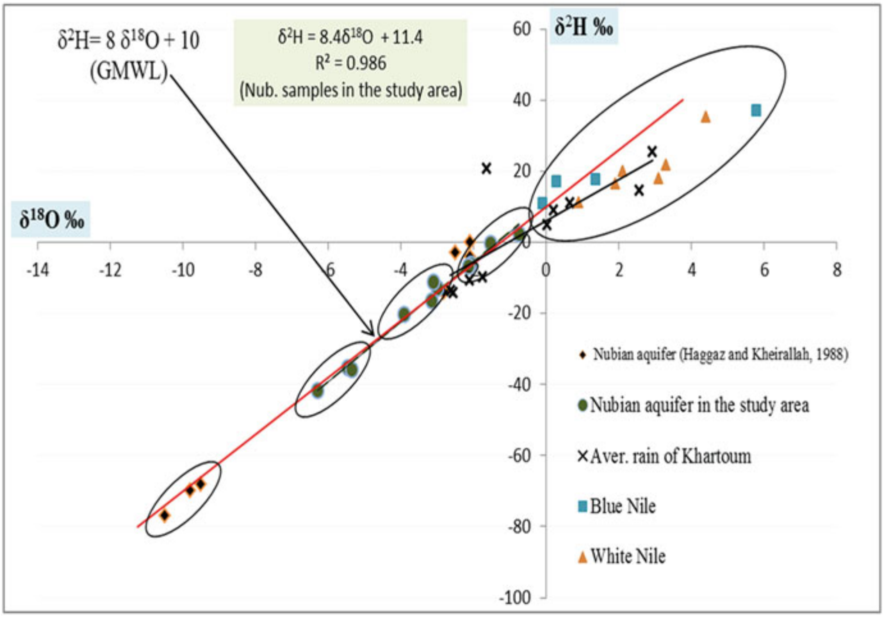


Fig. 16 Plot of $\delta^{18}O$ vs δD of average rains in Khartoum, Blue and While Niles, and groundwater in Gezira, Sudan (GMWL is from Edmunds et al. [62])

The isotopic composition of the groundwater samples of the study area shows increased depletion with increased distance from the Blue Nile. Furthermore, the more depleted isotopic composition, the more depth to the water level (see Fig. 17). This is an indicator of the influence of the recharge from the Blue Nile of heavy isotopic composition, which decreases with distance toward the west and southwest of the study area. Haggaz and Kheirallah [64] concluded that the Nubian aquifer east of the Blue Nile seems to be receiving slow recharge from the Blue Nile to a distance of not more than 13 km. Also, there are strong evidence indicating that the water of the Nubian aquifer is mixed with water of heavy isotopic contents. Many studies were conducted on the Nubian aquifer in North Africa, especially in Libya, Egypt, and Sudan. Moreover, all studies confirmed that the isotopic signature of late Pleistocene paleowaters of the Nubian aquifers is −11‰ in Kufra basin and ranges between −10 and 11‰ at the Egyptian oases [64, 67, 68].

According to the present results of isotopic contents compared to the previous studies on paleowater of the Nubian aquifer in the three countries (Sudan, Egypt, and Libya), the groundwater of the Nubian aquifer in the study area is renewable.

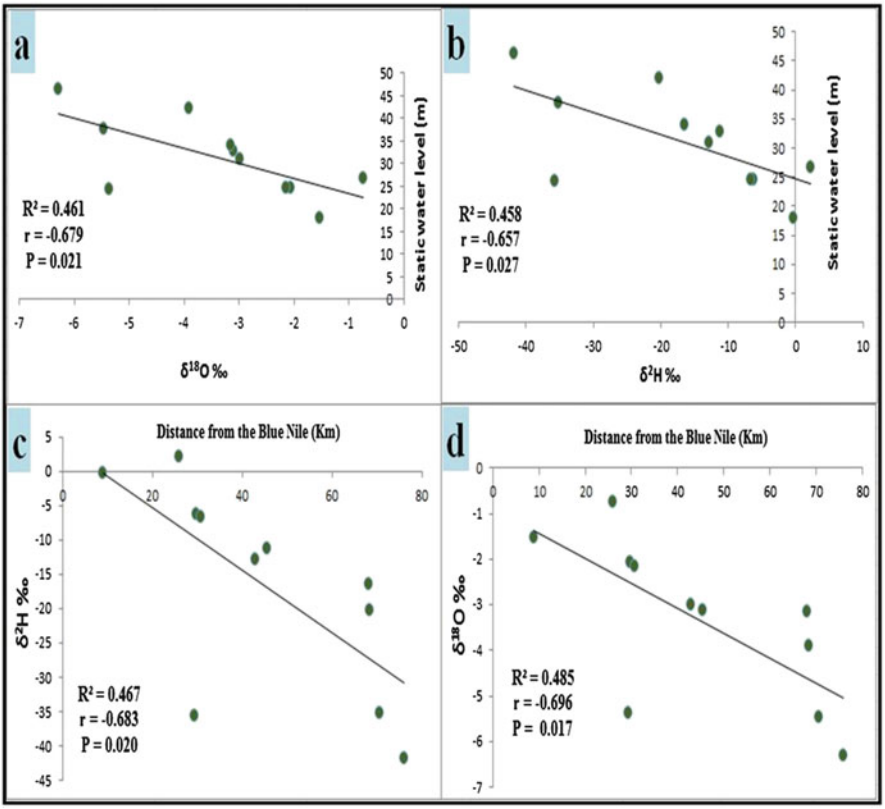


Fig. 17 The relationships between isotopic composition of the Nubian aquifer: (**a**) δ^{18}O vs static water level (**b**) δ^{2}H vs static water level (**c**) δ^{2}H vs distance from the Blue Nile (**d**) δ^{18}O vs distance from the Blue Nile

10 Summary and Conclusions

The Gezira is an occupied part of the most significant agro-economic project in Sudan. It extends along the west of the Blue Nile, and most of them lie in Gezira State and other small areas in the Blue Nile and Sennar States. The study area is distinguished by flat plain and sloped gently toward the north and the west. It is characterized by long hot, dry season for 8 months and short rainy season for 4 months. It is covered by Quaternary deposits of the Gezira Formation that is capped by recent superficial deposits in some areas. The Gezira Formation consists of clays, silts, sands, and gravels, while the recent superficial deposits composed of wind-blown sands and Khor deposits. The Nubian Formation of Mesozoic age is unconformably overlain the basement rocks and unconformably underlain the Gezira Formation. The Precambrian basement rocks are represented southwest of the study area.

There are two main aquifers in the area of study, the Gezira aquifer and Nubian aquifer. The best water-producing horizon is the coarse gravelly sands. The saturated thickness ranges between 18 and 25 m. The thickness of the Gezira Formation varied from about 10 m around El Manaqil and vicinities areas to more than 100 m south of Abdelaziz.

The Nubian aquifer deposits consist of sandstone, gravelly sandstone, and intercalation from mudstone and limestone. It is a confined aquifer that is covered by Gezira Formation, but around El Manaqil, it occurs under the unconfined circumstance. The water-bearing layers are consisting of sandstone and conglomerates. Its thickness is variable, ranged between zero and 40 m southwest El Manaqil as a result of shallow depths of basement rocks. The Gezira and Nubian aquifers are interconnected.

The piezometric water level map for the Nubian aquifer was constructed using the measured water levels of the wells taping the Nubian aquifer in 2013. It illustrates the piezometric levels varying between 369.4 and 406.6 masl. The main flow directions are east-west and east-southwest. Furthermore, the piezometric levels near the Blue Nile are higher than those away from it toward the west and southwest of the study area.

The temperature of the groundwater samples shows regular records where the maximum was 35.2°C while the minimum was 28.5°C. The values of pH range from 6.8 to 7.7. The salinity of groundwater increases away from the Blue Nile to the west. Most of the significant ions show the same manner of the salinity values, which are increasing away from the Blue Nile to the west and southwest of the study area.

The results of the heavy metal analysis for the ten groundwater samples of the Nubian Sandstone indicate that the all records are acceptable except iron in some locations.

The groundwater quality of the Nubian aquifer is suitable for drinking and all domestic purposes, except water of well No. 25 that is showing slightly increasing in salinity with a value of 1,070 ppm due to local geology condition.

Stable isotope (δ^2H and $\delta^{18}O$) signatures of the groundwater samples of the Nubian aquifers indicate that the groundwater is renewable and the Blue Nile is the main source of recharging. The influence of this recharging is not clear at the west of the study area away from the Blue Nile. The more distance from the Blue Nile and increase the depth to the groundwater level, the more depletion of stable isotopic contents.

The salinity content decreases toward the Blue Nile. The piezometric water levels are higher near the Blue Nile. The stable isotopic composition of ^2H and ^{16}O in the groundwater shows depletion with increasing distance from the Blue Nile. All the above results prove the direct recharge from the Blue Nile to the Gezira groundwater aquifer. The Blue Nile water flow will be entirely controlled by the GERD. Therefore, the GERD will increase the recharge because it will keep water in the Blue Nile always at a high level all year, resulting in increasing the seepage to the aquifer. The agriculture in Sudan will also be all over the year, so water infiltration to groundwater will be increased. The same effect has occurred in the

Nile Valley and Delta in Egypt since the construction of the Aswan High Dam, where the water level of groundwater increases with time.

11 Recommendations

Groundwater is significant for the people in Gezira area. The Blue Nile recharges the groundwater aquifer during the flood period from July to October. The construction of the Grand Ethiopian Renaissance Dam (GERD) will control the Blue Nile flow and increase the recharge. The other environmental, economic, and social effects of the GERD on the downstream countries should be investigated. A comprehensive monitoring program through observation wells is required to monitor the groundwater levels for evaluations of the quantity and quality of groundwater and its interaction with surface water of the Blue Nile. The consequences of the GERD failure or collapsing need detailed study to investigate all the impacts in Sudan and Egypt.

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Update, Conclusions, and Recommendations for Grand Ethiopian Renaissance Dam Versus Aswan High Dam: A View from Egypt

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Abstract This chapter summarizes the key information and findings for the book *Grand Ethiopian Renaissance Dam versus Aswan High Dam: A View from Egypt*. Also, the major conclusions and recommendations are provided. Some findings from a few recently published research work related to the covered themes as an update for the information covered in the book are reviewed and presented. Also, the main current challenges facing Egypt due to the construction of the Grand Ethiopian Renaissance Dam (GERD) due to the probable improper operation without cooperation with Egypt and Sudan are provided. The chapter is meant to provide a brief synopsis of some of the issues that have been identified in the construction of the Grand Ethiopian Renaissance Dam (GERD) including how these will impact the existing Aswan High Dam (AHD) and Egypt's water resources and the society as well. Varieties of negative and positive impacts of both GERD and AHD are summarized. Modeling analysis of these impacts into the future is also characterized and assessed. For instance, it has been shown that, depending on its initial impoundment plan and operational policy, GERD can have significant impacts on the downstream, for which the associated costs have not been taken into consideration. In particular, operating GERD solely for hydropower energy maximization involves extremely high risks for the downstream, particularly Egypt which depends almost on the water coming from the Nile. Based on the information, investigation, analysis, findings, and writings throughout this book, a set of conclusions and recommendations are presented.

Keywords AHD, Aswan High Dam, Cooperation, Egypt, Environmental impacts, Ethiopia, GERD, Grand Ethiopian Renaissance Dam, Modeling, Social impacts, Sudan, Win-win-win

1 Introduction

The purpose of constructing dams differs from upstream to downstream countries. On the one hand, in upstream countries, it is mainly constructed for generating hydropower according to their high altitude and to changing cultivation from rainfed agriculture to irrigated and continuously intensive agriculture. On the other hand, downstream countries construct dams mainly for long-term water storage for drinking and irrigation purposes and to control flooding. Considerations of upstream countries when constructing a dam differ from those of downstream countries, especially causing significant hazards to the next downstream riparian countries. The upstream countries should conduct studies related to the environment and socioeconomic impacts of the proposed dam to share with those downstream before beginning its construction process to help the downstream countries to mitigate the expected minimized harm, particularly the great reduction of water resources of downstream countries if they are almost dependent on the surface water coming from the river as in Egypt's case.

Egypt depends on the Nile for 97% of its water needs, although 85% of the river flow in Ethiopia. Egypt has for a long time held the major ownership of water from the Nile. Sharing of the already scarce water resources of the Nile River (NR) may become a serious security challenge in the near future. "The amount of fresh water available in Egypt 'may drastically fluctuate' in the coming decades due to factors like global warming and rising ocean temperatures, compounded by the construction of the Grand Ethiopian Renaissance Dam" (https://www.madamasr.com/en/2017/03/16/news/u/nile-deltas-increasing-salinity-an). It was opposed to the construction of any huge storage dam in Ethiopia without coordination with Egypt and Sudan to avoid or minimize the expected possible harm to the downstream countries. On the one hand, the Grand Ethiopian Renaissance Dam (GERD) being constructed by Ethiopia was formerly known as the Millennium Dam. The GERD is located in the Benishangul-Gumuz Region of Ethiopia on the Blue Nile, away from the Sudan eastern border by about 20 km [1]. The Ethiopian Electric Power Corporation (EEPCO) owns the project. Construction of GERD started in April 2011 and was initially expected to be completed in July of 2017, but it is still ongoing. The government of Ethiopia is funding the project, which will not only serve Ethiopia but Sudan too with an expected much harm to Egypt. At the end of the project, the GERD will be the largest dam in Africa. On the other hand, the AHD is a rock-fill dam, with a grout curtain and is fitted out with a diversion canal on the eastern bank of the river. Currently, the AHD electric power station is still the largest hydropower station in Africa. From its construction until July 2014, the AHD has generated more than 353,779 million KWH. However, the GERD will reduce the capacity of the AHD. There will also be several other impacts to the region (both positive and negative) related both to the environmental components and to the social components in Egypt.

This chapter presents basic information on both GERD and AHD and the main impacts as well. Studies confirm that the AHD has many advantages to Egypt compared to its adverse impacts while the GERD negative impacts to Egypt could be disastrous during the years of filling and in case the GERD collapsed. The situation will be more severe if the filling takes place during a low inflow period and no sufficient water Lake Nasser. The report of the International Panel of Experts (IPoE) pointed out some of the damage that GERD can cause to the downstream countries especially in the light of the shortage and severe imbalance in the water and environmental and engineering impacts of GERD [2]. This, in turn, confirms that GERD does not agree with the principle of "no harm" as one of the governing principles of international rivers [3, 4]. These issues will be discussed in detail in this volume. These impacts both now and into the future were discussed in the various chapters of this volume and will be summarized in this chapter, and recommendations will be compiled.

Therefore, the intention of the volume is to present an overview of the major impacts of GERD versus AHD by presenting the results of the latest findings of scientific research of Egyptian scientists and researchers through covering the following main themes:

- An overview of GERD versus AHD
- Environmental impacts of AHD
- Modeling the impacts of GERD on AHD and its downstream
- Environmental and social impacts of GERD on Egypt
- Assessment of the sediment of the AHD reservoir
- Maximizing the benefits of AHD reservoir
- International aspects of AHD and GERD

The next section presents a brief overview of the important findings of some of the recent (updated) published studies on the GERD versus AHD and then the main conclusions of the book chapter in addition to the main recommendations for researchers and decision-makers. The update, conclusions, and recommendations presented in this chapter come from the data presented in this book.

2 Update

By 2025, Egypt will face nationwide shortages of water at alarming rates. Decreasing freshwater supplies and the increasing salinity level of the Nile Delta's agricultural land [5] threaten to make the country uninhabitable by 2100. Water shortages have been noted in some areas of Egypt in recent years and will be further exacerbated by climate change. The proposed mitigation actions could include operating the Grand Ethiopian Renaissance Dam (GERD) by a committee from Egypt, Sudan, and Ethiopia to minimize the harm of the improper operation to the downstream countries, reducing evaporation losses from Lake Nasser, maximizing the use of groundwater wells and rainwater in Egypt, seawater desalination, sewage treatment and reusing irrigation water, maximizing water use efficiency, and starting giant projects out of the narrow valley and delta. Adopting all or a combination of the suggested management actions and strategies could slightly reduce the impact of GERD on Egypt. When discussing the mitigation of negative impacts, there are always three categories to be considered in the following order: avoidance, minimization, and compensation. The following is the major update for the book chapters.

2.1 An Overview of the AHD and GERD

The Nile supplies Egypt with almost 97% of its water resource. Therefore, without the Nile, Egypt will die. It is well known that almost all the cultural and historical sites of Ancient Egypt are found along its riverbanks. On the one hand, the AHD was built not only to control floods but also to achieve other objectives such as satisfying industrial power demand, developing Egypt's agricultural expansion plans, and navigation improvement. The overall impacts of the AHD construction can be classified into four broad categories: physical, biological, economic and social. This classification is to some extent subjective since many of the impacts are often interrelated, and some of them may spawn effects of other types. On the other hand, construction of GERD imposed additional challenges to Egypt due to the expected harm to all sectors in Egypt, particularly the agricultural sector, which consumes about 80–85% of the freshwater.

2.2 Environmental Impacts of AHD on Egypt Between the Last and the Following 50 Years

The AHD has now been operational for 50 years. Analysis of the AHD impacts obviously indicates that overall, they have been overwhelmingly positive for Egypt. Based on data gathered over the past decades, environmental (positive and negative) impacts of the AHD are discussed. Since 1964, this annual rate has ceased to reach the soil surface, with the following consequences. The AHD has accelerate the coastline erosion (due to lack of sediment brought by the Nile) in Egypt. Problems created by sedimentation are lake infilling, erosion downstream of the dam, deepening of the Nile Delta, and loss of nutrients to farmlands and Delta estuary. The incidence of schistosomiasis or bilharzia increased due to the AHD blocking the natural fluctuations in water height. The (positive and negative) analysis of selected impacts made in this chapter should provide a clear indication of the difficulties of assessing impacts of any large hydraulic structure. The dam increased Egypt's water quota from the Nile by 7.5 BCM by stopping the freshwater release to the sea [6]. The AHD provided Egypt protection against drought and flood. A unique microclimate (reservoir ecosystem), created by the reservoir, prevails in this region. The microclimate is characterized by a higher incidence of cloud cover directly over the water, lower air temperature, higher wind velocities, and an increase in relative humidity of the region. These meteorological anomalies are much localized and do not influence the environment surrounding the reservoir.

2.3 Importance of AHD to Egypt

The importance of AHD to Egypt's economic survival was demonstrated, at least qualitatively, during the 1980s. It is not too difficult to hypothesize what would have happened to the Egyptian economy and sociopolitical conditions if the dam had not been there to protect the country from, first, the potentially catastrophic impacts of a prolonged drought from 1979 to 1986 and, second, immediately thereafter the abnormally high summer flood of 1988, which had devastating effects on Egypt's upstream neighbor on the Nile Basin, Sudan. Even with the AHD in place, Egypt had come perilously close to experiencing the catastrophic impacts of the drought by early 1988, due to a dangerously low water level in Lake Nasser [7].

2.4 Impacts of Constructing the GERD on the Nile River

The NR is one of the trans-boundary rivers, which face these conflicts. The NR, which is shared by 11 riparian countries, is the life artery for water demands, particularly the downstream countries, i.e., Egypt and Sudan. The NR runs through very different climatic regions. Due to climate change and variability, the amount of water in the Nile Basin may fluctuate, and water availability is vulnerable. The NR Basin is characterized by water scarcity, population growth, and poverty that will likely cause the future to be very uncertain. Development projects in the basin countries including irrigation projects, hydropower dams, and other water diversion projects may cause conflicts between riparian countries [8]. Constructing water control structures on the NR basin will affect the riparian countries especially the downstream countries. Taye et al. [9] concluded that the region is encouraged to share data and information with respect to hydro-solidarity principles, which encourage equitable and reasonable utilization of international watercourses. Mohamed and Elmahdy [10] showed that the major faults which cross-cut the northern and southwestern hills are parallel with the faults that cross-cut the GERD site, and their displacement directions are perpendicular to the GERD walls, creating some alarm. Furthermore, studies on the hydrological, environmental, and social impact of the dam in the area and the communities are mandatory.

2.5 Stochastic Investigation of the GERD-AHD Interaction Through First Impoundment and Beyond

A stochastic framework is applied to overcome the two shortcomings on the impacts of GERD on AHD water availability as well as hydropower generation. To assess the full probability distribution of the different impacts of GERD, a large number of simulations with equally probable inflow sequences are needed. These equally probable flow sequences are generated using a suitable method that ensures the preservation of the intrinsic stochastic properties of the historical flow sequence, including Hurst exponent. The resulting values of different impact indicators will also be equally probable and can thus be used to construct the full probability distribution of these indicators. It is to be noted that because of GERD regulation of the Blue Nile flow and interception of most sediment, Sudan dams on the Blue and the main Nile would, in general, be operated at higher levels throughout the year, since there would be no need for much regulation or sediment flushing [11] provided that the GERD will be operated based on a cooperative mode between Ethiopia, Sudan, and Egypt and the normal natural flows of the Nile is guaranteed. This would result in an increase in evaporation losses between 0.5 and 1 km^3 depending on the new levels. The GERD reservoir maximum volume is taken as 74 km^3 at a maximum level of 640 m, with a maximum surface area of 1,904 km^2 [11]. Although some recent studies give a total reservoir volume of 79 km^3 [12], the most commonly reservoir volume used was 74 km^3.

2.6 Model-Based Optimization for Operating the GERD on the Blue Nile

Dynamic multi-reservoir coordination rules are possible and are available through the system optimization model. System optimization encompasses four sub-models pertaining to (a) streamflow forecasting, (b) river and reservoir simulation, (c) reservoir optimization, and (d) scenario assessment. It is targeted to identify a group of operational rules for the GERD that maintains minimum impacts on AHD in terms of the water deficit of downstream AHD and the generated power of the Aswan hydropower complex. The best operating rules will be arranged per the flood period type, storage capacity of GERD, and the initial levels of both dams. Several GERD regulation policies are formulated and assessed throughout this study. The baseline policy focuses on Ethiopian hydropower interests with GERD operating to meet a constant energy target [13]. Other policies are also implemented aiming to balance Ethiopian as well as downstream interests and to provide relief during periods of water shortage. This relief may be enabled by a certain amount of GERD storage (e.g., 10 or 20 BCM) reserved for this purpose as a cooperative regulation policy.

2.7 GERD Failure Analysis and the Impacts on Downstream Countries

One of the major impacts is the impact of the surge wave generated due to dam failure or generated in case of rapid dam evacuation due to any unforeseen circumstances. The surge wave depth to be expected due to dam break is compared with the total dam height and traveling at very high speed. Accordingly, very devastating impacts may occur in the downstream-developed areas. Such damaging force can cause fatalities, especially if there is no early warning and no emergency evacuation plans. In the case of GERD, the dam break analysis is very crucial due to the huge size and large dimensions of the dam [14]. In addition, the high risk of soil instability in the site location leads to a high probability of failure associated with GERD. GERD is located on one of the major tectonic plates and faults in the world. Around that fault, about 15,000 earthquakes are documented in Ethiopia. During the twentieth century, about 16 earthquakes with a magnitude higher than or equal to 6.5 occurred in Ethiopia at the fault, which cause severe damages. Several assessment scenarios and cases are investigated in this section to assess the impacts of GERD main or saddle dam failure on AHD and its downstream floodplains and structures. The assessment reveals the following outcomes:

- There is no significant difference between GERD main or saddle dam failure regarding the impacts on AHD.
- There are no negative impacts on AHD and its downstream floodplains and structures due to GERD failure in case of empty AHD reservoir as the maximum water level will not exceed the maximum allowable level and the maximum release to the downstream will not exceed the safe limit.

2.8 Environmental Impacts of the GERD Project on Egypt's AHD Reservoir and Mitigation and Adaptation Options

The most important question to answer is: Will the GERD affect Nasser Lake? It is believed that the construction of GERD will affect the Egypt's water quota through decreased discharge from the AHD [15]. The main adverse impact in Egypt will be a severe reduction in the water resources of Egypt and a reduction in power generated at the AHD due to a fall in water levels of Nasser Lake. Furthermore, the AHD will reach the minimum operational level during four consecutive years in the case the first filling of the GERD occurs during dry years, which would significantly affect the water supply to Egypt. The factors that affect of the GERD project on AHD are a reduction in the water share of Egypt; reduction in power generated at AHD; increase the salinization of Egypt's agricultural lands; increase in seawater intrusion; environmental degradation; and in filling lake Nasser/Lake Nubian with sediment. Increase in seawater intrusion in coastal aquifers in the North Delta has been threatening groundwater quality and increased salinity in these reservoirs [10]. A number of management actions and strategies are suggested to secure Egypt's water demands and to minimize the water scarcity problems. The actions identified are reducing evaporation losses from Lake Nasser, maximizing the use of groundwater wells and rainwater in Egypt, seawater desalination, sewage treatment and reusing irrigation water, maximizing water use efficiency, and starting giant projects out of the narrow valley and delta. The expected total amount of saved water using all the above strategies could amount 40 BCM [14] but will be consumed due to the rapid increase in the populations. Adopting all or a combination of the suggested management actions and strategies could reduce the impacts of GERD on Egypt, but the cooperative mode of GERD operation should be active.

2.9 Grand Ethiopian Renaissance Dam, Agriculture, and the Rural Poor in Egypt

On the one hand, the agricultural sector plays a significant role in the Egyptian economy. It is contributing 11.3% of total GDP and 13.1% of GDP excluding petroleum in 2014/2015; though decreasing, it continues to grow at a growth rate of 3% [16]. In addition, industries related to agriculture, such as processing, marketing, and input supplies, account for another 16% of GDP. The share of agriculture in exports is also substantial, accounting for about 10.3% of total exports and about 15% of nonpetroleum exports in 2015/2016 [17]. Agriculture is also a key sector since it provides livelihoods for about 50% (50 million) of the population living in rural Egypt. However, the annual population increase is contributing to a continuous decrease of the per capita share in agricultural land that dropped from 0.29 feddan in 1950 to about 0.10 feddan since the 1990s [18] which is one of the lowest in the world and thus affecting food self-sufficiency. On the other hand, the assessment of the impacts of GERD filling on Egypt under the different scenarios showed that water shortage severely impacts agricultural production and the Egyptian economy as a whole, as well as affect the local farming communities.

2.10 Assessment of Sediment Deposition in AHD Reservoir During 50 Years (1964–2014)

During the last century, many dams exist along the NR for various purposes. The existing reservoirs, especially those on the Blue Nile, Atbara, and the main NR, are seriously affected by sediment deposition at unexpected rates. Currently, for some reservoirs, costly sediment control measures are being practiced. The decision of postponing the problem by heightening the dam has been taken, and the unresolved situation is waiting for those in the design and planning stage. Also, the AHD, though large, is facing the problem of 100% trap efficiency. Further, in Sudan, Ethiopia, and Uganda, new dam projects are underway or have been proposed. As for the AHD, it created a reservoir behind it, which is Aswan High Dam Reservoir (AHDR) [19, 20]. The AHDR is the second largest human-made reservoir in the world. The reservoir extends from the southern part of Egypt to the northern part of Sudan. The AHDR has a total length of about 500 km (350 km inside Egypt and 150 km inside Sudan), the average width of the reservoir is about 12 km, and its storage capacity is 162 billion m^3.

2.11 Evaluation of Merowe Dam's Effect on the Accumulated Sediment in Lake Nubia, Sudan, Using RS/GIS

Some previous studies were concerned with studying the current state of the Nile Basin reservoirs' sediment, for example [21]. Constructing the Merowe Dam upstream AHD, as an example, reduces the incoming sedimentation rate per year into Lake Nubia dramatically as they trap part of the suspended sediment load every year in its created reservoir (Merowe reservoir) and consequently reduces the sediment budget. However, the capability of combining RS data with in situ measurements, using GIS analyst tools, to estimate and analyze sediment patterns in lakes has been proven in several studies [22, 23]. It is evident that the annual sedimentation rate was reduced by about 2.57 million m^3 (from 126.21 to 123.64 million m^3 before and after Merowe Dam construction, respectively) using the RS/GIS approach. Also, results indicated that the present approach overestimated the annual sedimentation rate by about 1.48% and 1.44%, before and after dam construction, respectively, compared to the results of the traditional method adopted by AHDA [24]. The present approach overestimated the reduction percentage in the annual sediment rate in the study area due to the construction of the Merowe Dam by about 3.5%, compared to the results of the traditional method adopted by AHDA [24].

2.12 Dredging Clay of the Nile: Potential Challenges and Opportunities on the Shores of the AHD Reservoir and the Nile Valley in Egypt

Some authors, e.g., Abela and Favila [25], have recommended dredging sediment from bottom reservoirs to enrich poor soils. The levels of trace elements and heavy metals must be assessed in the grown crops to comply with standards for food. Clays of the AHDR are smectite based with kaolinite as a secondary component [26]. Past experience with this type of clay with a high plasticity index indicates that cutting leads to stiff balls. Clay balls increase friction losses in the dredging pipelines. A hydraulic analysis is presented to investigate the requirements for dredging large quantities for the establishment of new villages and communities with a set goal of dredging 100 million m^3/year or as the average rate of sedimentation has been around 140 million m^3/year since 1965. The effort would emulate on a larger scale the COAST 2050 project in the USA, an effort to rebuild the shore of Louisiana in the USA through dredging and cultivation and estimated to cost $15 billion dollars but could be brought down to an appropriate cost through the development of national industries.

2.13 Harvesting the Skies of Egypt: An Option to Recover the Evaporation Losses from the AHDR

While the AHDR has protected Egypt in periods of acute drought, its extended surface of 6,000 km^2 causes a tremendous evaporation loss of water amounting to 20% of the entire domestic, agricultural, and industrial consumption. In the last 50 years, a number of efforts have been made to catch moisture from the air. Dew forms on cold nights on the glass shields of millions of cars in Egypt, but there are no collectors to collect it into potable water. The greatest challenge is to slow down the movement of water vapor from the evaporation back to the tropics. Northerly wind due to the Hadley Cell and Coriolis forces because of earth's rotation force the moisture toward the Red Sea Coast and the equator feeding back indirectly the very same GERD that will deprive Egypt from a percentage of water it used to receive. Weather modification [27] is, therefore, an option if not the only option to capture some of this valuable moisture through collaboration between Egypt and Sudan. There is no model to copy, and both countries will have to embark into experiments of their own. The conditions favor high-altitude weather modification at 4,000 m with very careful planning. Cloud formation over the AHDR is at its peak during the flood season of July and August, while it is at a minimum over the north coast of Egypt. This opens an opportunity to maximize utilization of the aircraft.

2.14 Impact of the International Context on the Political and Legal Dimensions of the AHD (1952–1960)

Since the AHD was the most excellent strategic base for all developmental projects in Egypt, the study raises a question that represents the core of the research problem: What is the effect of the international context (the regional and global) on the political and legal dimensions of the AHD? One of the most important political and legal issues about the AHD project raised by the World Bank and Britain was that the Nile River is an international river; therefore, the river basin countries must approve it before proceeding with its implementation. It was clear that the international context was the determining factor in influencing the political and legal dimensions of the AHD in Aswan. Naturally, Egypt and Ethiopia were part of this conflict, and that led to bad relations between the two states. According to Egypt's Nasser, Ethiopia was a hostile state especially after it signed a military agreement with the USA in 1953 and received an Israeli general consulate to Addis Ababa in 1965. As a reaction, Egypt assisted the Eritrean separatists and backed Somalia during its conflict with Ethiopia. Also, Egypt encouraged the "Grand Somalia" notion to weaken the Ethiopian front and ban it from using the Nile to pressure Egyptian policies [28]. In an unstable political climate, it was difficult to reach political solutions that may serve the legal side, although the effects of the AHD were exclusively limited to the Egyptian and Sudanese sides [29].

2.15 *The Continuous Dispute Between Egypt and Ethiopia Concerning Nile Water and Mega Dams*

During the negotiation talks between Egypt and Ethiopia, the standpoint of Egypt is that Ethiopia should omit the saddle dam ultimately to decrease the water store capacity. This will raise the efficiency of generating electricity to more than 65%. This also may end the dispute or the future conflict with Egypt when the impact of this substantial oversize dam touches everyone in Egypt. However, and in the same trend, Egypt bears several accuses from Ethiopia like their falsely accuses such as as follows: Egypt cultivates rice even if it is a desert country. Egypt just cultivates a heavy clay soil in northern Nile Delta land not exceeding 1–1.5 million acre to control the salinity building up that threatens Delta [2]. Rice cultivation becomes the only way to leach out the salt accumulation and prevent land degradation after preventing the flooding by High Dam.

Despite the dispute between downstream and upstream countries, they should look for a framework for collective work to tame the loss of water in the basin swamps and wetlands. Only 4% of the catchment water and precipitation in the upstream reached to the Nile stream, while more than 1,600 BCM is running outside the NR course. The water harvesting and taming of swamp water may add more than 100 BCM of water to the Nile stream, which can solve most of existing water requirement problems between Ethiopia, Sudan, and Egypt. The GERD could be welcome if Ethiopia omits the saddle dame or lowers its high to be between 20 and 30 m instead of 50 m, which may reduce the storing capacity to 25–30 BCM instead of about 74 BCM.

2.16 GERD and the Ethiopian Challenge of Hydropolitical Hegemony on the Nile Basin

The current developments of the GERD file have imposed an urgent necessity for analyzing the hydropolitical scene in the Nile Basin and the political and legal problems that arise from Ethiopia's non-compliance with the "no harm" or "prior notification" principles before implementing this huge project. It became clear that Ethiopia's main aim of the construction of GERD on the Blue Nile is primarily a political-strategic one; the aim is to achieve "hydropolitical hegemony" in the Nile Basin. Although "hydro-hegemony" can be interpreted within the framework of the realist school of international relations, yet international relations theories require development to deal with international water issues. This development is specifically required to understand and interpret international interactions – whether based on struggle or cooperation – that are related to hydro-hegemony in a way that avoids the current discourse about "water wars" and "water peace." Hydro-hegemony can involve either "enlightened leadership or repressive hegemony." Hegemony can provide order and stability to ensure water flow to the major states, and on the other side, the hegemony may be accompanied by exorbitant costs for the weaker states in the political equation, resulting in the lack of control on the organization and management of the river decisions and absence of appropriate allocation of water for those states. This may cause political unrest, opening the door for severe water conflicts. The negative type of the hydropolitical hegemony refers to "the conflict of departments, political and geo-strategic interests between upstream and downstream states, where the upstream states use the water to get more power, while the downstream states use power to get more water" [30, 31].

2.17 The Impact of the GERD on Gezira Groundwater, Sudan

Groundwater in Gezira is stored in metal boxes before distribution via tubes to the public, which is checked periodically to meet the standards of water quality and to prevent any health hazards. Also, higher salinity, especially in the central Gezira at El Manaqil and its neighborhoods, was recorded. Moreover, the absence of observation wells, which allow more control and management for the aquifers in the study area, is a big problem. Elkrail and Omer [32] designed a conceptual model for numerical flow simulation, the aquifer potentiality, general groundwater flow direction, and the primary source of recharge in Abu Quta Area, Gezira State. They concluded that the river leakage represents 58.0% of the total inflow indicating the main source of recharge. The groundwater in the Gezira area occurs in two principal aquifers: the Gezira formation (Quaternary aquifer) and the Nubian sandstone formation (Cretaceous aquifer). The outcrops of basement rocks represent the local recharge area for the water in El Manaqil and southern Gezira areas.

3 Summary and Conclusions

Throughout the course of the current volume, the editors were able to reach several conclusions. Besides methodological insights, the chapter originates key lessons from the cases in the book, in particular, the promising characteristics of the available GERD-AHD simulation model, which was used in assessing the impact of GERD on AHD operation. These conclusions are important to understanding key for GERD versus AHD situation. The following conclusions could be stated based on the materials presented in all chapters of this volume:

3.1 Environmental Impacts of AHD

Two chapters are presented related to the environmental impacts of the AHD. Any large infrastructure like the AHD invariably has positive and negative impacts to a varying degree. The AHD is now being operational for 50 years. However, the positive attributes of the dam were considered to outweigh the negative consequences. The AHD has been instrumental over the years in protecting Egypt against drought. AHD benefits include (1) production of electricity, (2) providing water for agricultural land reclamation, (3) converting basin irrigation with perennial irrigation, (4) expanding rice production, (5) development of a fishery in the reservoir formed by the AHD, and (6) improvement of river navigation due to steady water levels downstream from the AHD. The benefits of the dam include the hydropower energy generated, the increase in water available for irrigation and drinking water supply, flood regulation and protection, navigation, and enhanced tourism. Lake Nasser (the reservoir basin) has become an important fishing site, supplying food and livelihood for the population around it. The AHD helped regulate some of this flooding. The major advantage of AHD was creating a multiyear reservoir to enable water resources stability long-term. Throughout the drought period in Egypt (from 1981 to 1988 and from 2006 to 2017), the AHD played a vital role in water access. Also, the dam increased Egypt's water quota from the Nile by 7.5 BCM by stopping the freshwater release to the sea [6]. The dam has supported a high population growth rate in Egypt, because it encouraged an expansion of agriculture, promoted energy production, and allowed more energy for manufacturing. An important positive effect was that it enabled agriculture to move from basin irrigation to year-round irrigation, so crops could now be produced year-round. The AHD created a 30% increase in cultivable land in Egypt and raised the water table in the Sahara.

The AHD also benefits Egypt in supporting land reclamation and greening the desert. About 0.84 million hectares were reclaimed, irrigated, and cultivated using the water made available by AHD reservoir. Siltation of irrigation canals before the construction of the AHD was a large problem and ranged between 130 and 160 million tons every year [33, 34]. Siltation costs in Egypt were millions of pounds, which included the necessity to hire thousands of workers to remove the precipitated mud from the irrigation canal. The AHD prevents silt from passing through the regulated water stream from the front of the dam to the irrigation canals. Silt accumulation usually precipitates in the mouth entrance of the dam lakes and the first kilometers long on the lake. It was also reported that this siltation helps the drinking water companies to improve drinking water quality in Egypt due to trapping the sedimentation in the front of the AHD in the Sudan part. The construction of the GERD is expected to retain an important volume of silt and lower the levels of the water in the AHD reservoir by 2–3 m. Furthermore, although fish catch initially suffered, the catch steadily increased and reached a maximum of 34,206 metric tons by 1981 in Lake Nasser (was 2,662 metric tons in 1968). Records indicate that 1980–1983 were the most productive years when the annual fish catch varied between 28,667 and 34,205 metric tons [35–37]. After that, the catch began to decline. As a solution, the country transferred to aquaculture, which now represents more than 65% in 2017 of the total fish production creating more jobs in fisheries. Finally, conserving freshwater reserves was also beneficial to the economics of various sectors such as agriculture, industry, housing, and others. Increasing water supply for these sectors means increasing the productivity and creating a strong economic base. According to Strzepek et al. [38] and Bhatia et al. [39], the ADH total risk neutral benefit is estimated at LE 4.9 billion. The impact of capital shock in agriculture and transport is LE 1.1 billion.

3.2 Modeling the Impacts of GERD on AHD and Its Downstream

These two basic information are discussed in four chapters. Modeling is a useful tool for analyzing future impacts and scenarios. Several modeling efforts have been carried out to develop a better understanding of some of the impacts the GERD may have on the AHD and the downstream area after construction is completed. A stochastic analysis of the impacts of GERD on AHD is presented. Synthetic Nile flow series were generated using a fractional Gaussian noise (FGN) model to simulate 1,000 probable NR flow scenarios based on the current design of the GERD and AHD system. Results from the analysis indicate a very high downstream risk when GERD is operated as an annual storage reservoir. The following conclusions were drawn based on the results of the simulation:

- Simulations show that water abstracted by the GERD affects all other water balance components, and there was no actual saving for downstream countries. In particular, evaporation from the GERD does not become compensated by the reduction of evaporation from AHD. Overall, the simulations indicate a net increase in losses in the system with the addition of the GERD in the long-term.
- Operating the GERD to maximize energy power production would require large amounts of water for the GERD's first impoundment and involves higher GERD evaporation losses (compared to long-term regulation), resulting in a water deficit and thus less able to produce power at the AHD.
- Simple economic analysis reveals that AHD costs due to water deficit and hydropower energy reduction are of the same order of magnitude as GERD net benefits, and consequently there may not be an overall financial benefit, and downstream countries may suffer from this.
- The GERD reduces the ability of the water savings in the long-term, due to full water utilization by downstream countries. It is inevitable that both GERD and AHD would be drawn down to their dead storage at some point in the future. This would be caused by an extended drought period similar to or worse than the 1980s period. Refilling both reservoirs would be more challenging than the current situation of GERD first impoundment, while AHD is currently almost full.

Another chapter in the current volume investigate how the impacts of constructing the Grand Ethiopian Renaissance Dam (GERD) will affect three main regions of the NR, including the area close to the Sudan-Ethiopia border; near to Khartoum, Sudan; and the main Nile at the entrance of Lake Nasser, Egypt. The impacts are divided into hydrologic and environmental impacts. The study delineated the reservoir area to estimate the reservoir volume and its geometrical dimensions for from the time of dam construction until the full operation and storage capacity. Results show that the best accepted scenario for constructing the dam is by filling the dam reservoir with 10 BCM/year or less in 3.8 years. Furthermore, the impacts of a potential dam breach on Ethiopia and the downstream countries were studied by the authors using simulation applied in the river analysis system (RAS) model of the hydrologic engineering center (HEC-RAS). In the case of a dam breach, a severe flood will result in inundation of the Sennar Dam, Sudan, causing flooding 15 km wide and 200 km long, and the areas in between, until it reaches Khartoum, Sudan. Also, the water level is expected to rise 3 m from the dam until it reaches Nasser Lake. The authors found that the majority of the impact will occur after the construction and will transform the area from a free-flowing river ecosystem to an artificial water canal habitat. According to the HEC-RAS model results for all filling reservoir-filling scenarios, the water velocity will be reduced. Furthermore, the water temperature in the river will be colder than it should be, and these changes will impact other water characteristics such as chemical composition, dissolved oxygen levels, and the physical properties of the water which are often not suitable for the aquatic plants and animals that evolved with a given river system. "It would also result in increasing the pollution of the water streams and creating problems in the supply of water for drinking and industry" (https://egyptianchronicles.blogspot.com/2013/06/cairo-universitys-report-on-ethi). The authors predict that the GERD construction will have significant hydrologic and environmental impacts on the allowance of Egypt and Sudan from the Nile water.

An extensive investigation was applied using the GERD-AHD SIM model to determine the best operating policy for the GERD on the Blue Nile that would have the least impact on the AHD. The main objectives should be achieving a minimum water deficit in the downstream and a maximum power generation from both GERD and AHD. The results of the model were tabulated and analyzed using the mentioned criteria to obtain the best long-term regulation policies for GERD. The main two factors that affect the management of AHD due to the regulation policy of GERD are the total annual water deficit downstream AHD and the generated energy from AHD. The results of the model indicate that cooperative management scenario which preserves water storage in the GERD for the need of the downstream countries represents the best regulation option.

3.3 Environmental and Social Impacts of GERD on Egypt

Two areas are used to investigate the environmental and social impacts of GERD on Egypt. The first area seeks to investigate the probability of failure of the GERD, which is another important component that required modeling and statistical methods. The GERD failure simulation shows that the peak outflow at GERD approached 2 million m^3/s and occurred within 5 h from the beginning of GERD failure. Also, the peak inflow at the entrance of Lake Nasser approached 37,000 m^3/s and occurred within about 3 weeks from the beginning of GERD failure. The inflow to Lake Nasser is about three times of the maximum inflow at wet seasons (the maximum measured peak inflow during wet season was about 13,000 m^3/s), causing an issue for the AHD. Furthermore, the simulation showed that Roseires, Sennar, and Merowe dams would be washed if the GERD fails and Al Khartoum city will be flooded by 10–15 m above ground level. Other cities in the area could also be flooded or impacted, causing a risk to human life but also to the environment and the economy. The literature review and the collected data showed that the GERD has high failure probability due to the geological nature of its location.

Another area of concern is what the impact on the rural poor may be. This requires the analysis of the macro- and microlevel impacts. This includes an analysis of aggregated water and agricultural land reductions and their subsequent effects on crop value, imports, exports, and employment as well as to the government's policy to safeguard self-sufficiency in strategic crops as well as the sustainable livelihoods of farmers (landowners and laborers) in governorates with high poverty rates, in Lower and Upper Egypt. Currently, farmers in the rural poor areas do not have strategies for dealing with water shortages that may be associated with the dam impacts or the ability to deal with flooding in the case of dam failure, so the impacts on them may be severe. Evaporation losses at the AHD are transported at low levels of a few hundred meters but also at heights of 1,500–4,000 m as there are different patterns of lower and upper wind. The average volume of the annual water loss by evaporation is about 10 billions m^3.

3.4 Assessment of Sediment of the AHD Reservoir

Two methods for the assessment of sediment of the AHD reservoir are updated. The first chapter is an attempt to assess and analyze the deposition in the AHDR during the last 50 years from 1964 to 2014, by using different techniques (GIS method and the traditional method) to estimate the effective lifespan of the reservoir. The traditional method gives an overestimate in the calculation of deposit sediment by almost 10% in comparing by the GIS method. Total volume at level 175 in 2006 is 4.7 BCM using the traditional method, but GIS method gives 4.22 BCM for the same level. On the other hand, the total volume at level 175 in 2008 is 5.2 BCM using the traditional method, but the GIS method gives 4.68 BCM for the same level. It can be concluded that the traditional method gives an overestimate in the calculation of deposit sediment by almost 10% in comparing to the traditional method.

The second chapter evaluates the Merowe Dam's effect on the accumulated sediment in Lake Nubia. The aim is to estimate the annual inflow sediment rate into Lake Nubia before and after the operation of Merowe Dam. This will be achieved by utilizing remote sensing (RS) and geographic information system (GIS) techniques by utilizing the 3D profiles of Lake Nubia. The results of the present approach based on RS/GIS are compared to obtain results using the complementary cross sections. The results indicate that the annual sedimentation rate was reduced by about 2.57 million m^3 (2.04%). Also, results indicated that the present approach overestimated the annual sediment rate by about 3.50% before and after the operation of the Merowe Dam compared to the results of the method adopted by AHDA. This low reduction percent indicates that the effect of Merowe Dam on the reduction of the annual incoming sediment rate to Lake Nubia is minor and can be neglected compared to the effect of huge upstream dams such as the Grand Ethiopian Renaissance Dam.

3.5 Maximizing the Benefits of AHDR

Three basic approaches to maximize the benefits of AHDR are identified. Harvesting the skies of Egypt is an option to recover the evaporation losses from the AHDR. The governments of Egypt and Sudan should embark on weather modification to capture these losses. The clouds are overcast at 5–25% over Lake Nubia and Lake Nasser and will require a carefully planned approach. The technology of weather modification can also be tested on the north coast of Egypt from Salum to Rafah and certain parts of the Delta, where annual precipitation ranges from 50 to 200 mm/year. The ancient Egyptians, the Greek, and Roman rulers had developed in the past a complex system of deep wells and water storage schemes for storing rainwater that should be revived in parallel to weather modification schemes. Cloud formation over the AHDR is at its peak during the flood season of July and August, while it is at a minimum over the north coast of Egypt. This opens an opportunity to maximize utilization of aircraft all year around with an emphasis on the North Coast in the winter and on Lake Nasser in the summer. Weather modifications must be viewed as a carefully planned project. The conditions favor high-altitude cloud seeding at 4,000 m to avoid the errors and pitfalls of low-altitude failure.

In the particular context of Egypt, various scientists have estimated the loss of water by evaporation over the AHDR to be between 11 and 16 billion m^3/year. The variation depends on many factors such as fluctuation of floods, rain over the equator, siltation, and changes in the surface-area-to-volume (SAV) ratio. The construction of the Great Ethiopian Renaissance Dam (GERD) is anticipated to increase the surface area ratio through a decrease of water level between 0.4 and 0.75 m but also by capturing more sediment. By the Hadley cell and the meteorology of the Sahara, water losses due to evaporation tend to move south and southwest toward the equator. Thus, these losses find themselves drifting toward the sources of the Nile and feed the GERD indirectly. In the most pessimistic opinions, Egypt could lose 20–23% of its arable land due to the construction of the GERD. Egypt must, therefore, embark in all methods to recover water losses by evaporation over the AHDR. There are also other sources of moisture that come through wind over the North Coast, the Delta, and the northern Sinai as the result of evaporation of water over the Mediterranean Sea.

Community development by de-silting, the AHDR, is another approach identified to maximize the benefits of AHDR. De-silting the large reservoirs of the Nile such as the Roseries, Sennar, Girba, and the AHDR should be done at the national and international levels. These can offset the loss of reservoir capacity and increase evaporation losses due to the reduction of the surface-to-volume ratio, accumulation of weeds, and loss of hydroelectric power production due to sedimentation. A careful analysis of the sediment in Lake Nasser with a preponderance of plastic clay reveals a sensitivity to potential dredging. The plasticity indices satisfy the conditions for the formation of balls of clay that would slow down dredging. It is therefore critical for Egyptian engineers to develop the technology for pulverizing the plastic clay when cutting them. Egypt can also become a platform for the development of technologies for de-silting various reservoirs in Sudan and for training Sudanese engineers. Ultimately, these efforts can lead to the development of small communities.

3.6 International Aspects of AHD and GERD

Four chapters are devoted to address the international contexts of both GERD and AHD. The story of constructing the AHD had presented the role of each stakeholder either with or against the AHD, which was explaind and discussed in details. The different trials of Ethiopia to control the Nile are also explained and discussed with the frame of the law of the international rivers. The impacts and results of the dispute between Ethiopia and Egypt are well discussed. The fourth context is how the GERD will impact the groundwater in Gezira area.

The High Dam is the beginning and the real foundation for all development projects in Egypt. However, its establishment was linked to difficult and complex political and strategic conditions, because of the historical phase that Egypt witnessed at the local and international levels. At the local level, Egypt was undergoing a transition in its political history by moving from the monarchy to the public system and ending the dependence on British colonialism in full. At the international level, that period marked the beginning of the bipolar system, the escalation of the bipolar conflict, and the complexities of international and regional political interactions, particularly those relating to the Aswan High Dam.

It was clear that the international context was the determining factor in influencing the political and legal dimensions of the Aswan High Dam.

The West (USA-UK-WB) sought to exploit the funding of the project to impose a number of political demands on Egypt. When Egypt refused to comply with the requests of the American and British governments, the result was the decision to withdraw the World Bank funding the High Dam on July 19, 1956. The Soviet Union emerged on the scene of the political struggle over AHD and provided Egypt with political, financial, and technical support, which enabled Egypt to build AHD without succumbing to Western political conditionality. Overall, in terms of the legal dimensions of the Aswan High Dam, despite the legal problems raised by Britain, the United States, and Ethiopia, especially regarding the issue of “significant harm,” the AHD was consistent with the principles contained in the International Public Water Law of the International Rivers, and Egypt had complied with the “prior notification” requirement before building AHD.

On the other hand, the “Renaissance Dam” was one of the dam projects proposed by the US Bureau of Reclamation (USBR) report in 1964 on the exploitation of the waters of the Blue Nile. However, the developments in the GERD file recently witnessed an escalation of the conflict between the Egyptian and Ethiopian sides. It is well recognized that Ethiopia consumes time in negotiations and non-concessions with clear agreed outcomes.

Ethiopia has a number of declared objectives behind GERD, which are developmental goals. However, there are undeclared political and strategic objectives: imposing “hydroelectric hegemony” on the Nile Basin and achieving political and geostrategic leadership in that basin.

The Ethiopia’s announcement of the construction of GERD was a few weeks after the Egyptian revolution on January 25, 2011. The laying of the foundation stone on April 2, 2011 confirms Ethiopia’s quest to realize the dream of water hegemony over the Nile Basin, which has been the tyrants of Ethiopia for many centuries. Ethiopia seeks to dominate the Nile Basin through the establishment of a number of dams on the Blue Nile, unaware of the impact of these water projects on the water interests of Egypt; and on Egyptian water security.

The impacts are divided into two main categories, which are hydrologic and environmental impacts. By studying the hydrologic impacts, the best accepted scenario for constructing the dam is by filling the dam reservoir with 10 BCM/year or less in 3.8 years. Furthermore, the impacts of the dam breach on Ethiopia and the downstream countries are studied. In case of dam breach, a severe flood will result in inundation of the Sennar Dam, Sudan, 15 km wide and 200 km long, and the areas in between, until it reaches Khartoum, Sudan. Also, the excessive water level with 3 m rise is expected from the dam until it reaches Lake Nasser. By studying the environmental impacts, particularly those of the population displacement, carbon dioxide emissions, agricultural land, animals, and the aquatic life, we will gain a better understanding of potential risks.

The current and future water projects in Ethiopia or other Nile Basin countries can be a means of rapprochement between the basin countries if they are dealt with by the win-win approach. The aim of such approach is that the various basin countries should agree on development projects that generate energy for the source countries. This should be in a way that does not affect the Egyptian and Sudanese water quota while at the same time realizing the interests of all the people of the Nile Basin. However, this cooperative approach is subject to acceptance by the source countries of the requirement of prior notification before the implementation of any water projects. In constructing GERD, Ethiopia aims to achieve some developmental declared goals in addition to some undeclared political and strategic objectives. Among these objectives is the imposing of "hydroelectric hegemony" on the Nile Basin, which would consequently lead to achieving political and geostrategic leadership in that basin. In its turn, this would lead to sieging of Egypt politically and strategically near its African circle/region. Does Ethiopia aim to build GERD to achieve hydropolitical domination as well as development goals? What is the evidence? It is clear that the GERD file is witnessing an escalation of the conflict in hydropolitical interactions between the Egyptian and Ethiopian sides.

Despite the dispute between downstream and upstream countries, they should look for a framework for collective work to tame the loss water in the basin swamps and wetlands. Only 4% of the catchment water and precipitation in the upstream reached to the Nile stream, while more than 1,600 BCM is running outside the NR course. The water harvesting and taming of swamp water may add more than 100 BCM of water to the Nile stream, which can solve most of existing water requirement problems between Ethiopia, Sudan, and Egypt. Egypt has always received demands from the upstream countries to pay for water, which reflects the deep belief of them, as they owned the NR, which is not correct. Nile Basin countries have the capability to achieve the food security for all people and may for all African population, by efficiently using plenty of fertile land and the available water. The GERD could be welcomed if Ethiopia omits the saddle dame or lowers its high to be between 20 and 30 m instead of 50 m, which may reduce the storing capacity to 25–30 BCM instead of 74 BCM.

Environmental studies of the GERD effect on Egypt and Sudan are vague. The investigation of water interaction between the surface water of the Blue Nile will be controlled entirely by the GERD and the White Nile with Gezira groundwater aquifer. If there is a direct recharge from the Blue Nile, the GERD will increase the recharge because it will keep water in the Blue Nile always at a high level all year, resulting in increasing the seepage to the aquifer. Agriculture will also be all over the year, so water infiltration to groundwater will be increased. Results of hydrochemical data indicated that there are not any evidence of the groundwater pollution resulting from the anthropogenic activities. Moreover, away from the Blue Nile, the influence of recharge is negligible, but the water of the Nubian aquifer still mixed with water of heavy isotopic composition. The chemical and physical characteristics of groundwater indicate that the GERD will increase the recharge because it will keep water in the Blue Nile always at a high level all year, resulting in increasing the seepage to the aquifer. Agriculture in Sudan will also be all over the year, so water infiltration to groundwater will be increased.

The following are the major conclusions:

1. The GERD has severe adverse impacts on Egypt, particularly in the agricultural sector, which consumes the major portion of the available water resources of Egypt. On the other hand, the negative impacts of AHD are minor compared to those of GERD. Added to the above is the fact that GERD is in the upstream of Sudan and Egypt, while AHD is at the downstream of Sudan which means AHD has no negative impacts on the upstream countries.
2. The positive impacts of AHD to Egypt are numerous while those for GERD are of minor importance.
3. The AHD was consistent with the principles of “no harm,” “respecting acquired rights,” “prior notification,” “international cooperation,” “fair and equitable utilization,” “peaceful settlement of disputes,” “non-abuse of the right,” and “good-neighborliness,” but the GERD is violating all of these principles.
4. The AHD represented a model of cooperation between riparian countries in international rivers, where an understanding between Egypt and Sudan on issues related to the dam was achieved and codified in the “Convention of the full use of the Nile water” in 1959.
5. The analysis of hydropolitical behavior of Ethiopia on GERD proved that there is a correlation between the Ethiopian intransigence and the insistence on building GERD with the current specifications. The aim is to enable Ethiopia to have political control over the Nile, hence damaging the Egyptian national water security.
6. The analysis of Ethiopia’s conduct on GERD negotiations revealed that it seeks to consume and waste time in a planned manner while not making any concessions in addition to spreading contrived tension to the Egyptian side. Moreover, Ethiopia tends to divert the Egyptian side’s efforts into unimportant details while undermining the fundamental issue of Ethiopia’s responsibility to build a huge dam without prior consultation with the downstream state, Egypt.
7. Best operating policies of GERD should consider reserve storage for downstream countries and at least 10 years filling period.

8. Selection of the best operating policy of GERD should be based on the minimum water deficit downstream AHD. Downstream socioeconomic impacts, as well as environmental impacts, should also be considered in developing such operational policies.
9. To save more than 1 million m^3 of lost water from Lake Nasser, 0.500 km^2 must be covered with circular foam sheets with an efficiency of coverage equal to 90% if economically feasible.
10. Harvesting of the evaporation from the AHD could have great benefits to Egypt and Sudan.
11. Removing the sediment from the AHD could help in creating new sustainable communities.

4 Recommendations

A key aspect of GERD versus AHD situation is the ability to adapt to future challenges. We argue that despite the clash between downstream and upstream countries, sustainable systems need built-in flexibility to achieve the goal. Throughout the course of this volume, the editors noted some areas that could be explored to further improvement. Based on the authors' findings and conclusions, this section offers a set of recommendations providing suggestions for future researchers in exceeding the scope of this volume.

1. The Nile River supplies Egypt by 97% of its water needs, and, therefore, it is the artery of the life of the Egyptian. Without the Nile, there would certainly not have been the Egypt we know. Consequently, Ethiopia should cooperate with Egypt and respect the international rules and agree to protect the Egyptian life. At the same time, Egypt should be willing to support the Ethiopian development plan via its soft forces as much as possible.
2. The operation of GERD should be linked to the operation of AHD and should be operated cooperatively with Egypt and Sudan to minimize its negative impacts on the downstream countries.
3. Keeping in mind the importance of the cooperative mode between Egypt, Ethiopia, and Sudan, Egypt should seek and investigate the capability of Nile conservation projects to balance the amount of water reduction associated with proper operation and the development in the Blue Nile.
4. If still possible and applicable, the efficiency of the GERD and Border Dam needs to be studied and compared using sound economic analysis, in light of the high cost of GERD and the low efficiency in comparison to the low cost of Border Dam and high efficiency of power generation.
5. The potential negative impact of climate changes on the system and particularly on Egypt need to be investigated and considered in the negotiation.

6. Better data should be collected, especially for velocity distribution, wind speed, and bed load to enable the development of new communities around based on maximizing the benefits of AHDR.
7. A deep study of the discharge and the sediment load entering AHD watershed models, which link the sediment production and delivery in the upstream catchments to the sediment transport and deposition in the river channels and reservoirs, will be helpful for prediction of the future behavior of AHD.
8. The environmental impacts of any future upstream engineering projects on the Nile should be investigated thoroughly, and its effects on the amount of water discharge and sediment deposition in the AHD should be studied too, and then the decision of construction should be based on agreement with the downstream countries.
9. The cooperation between the Nile Basin countries could be achieved by different ways, e.g., by expanding cooperation to include development sectors in all political, security, economic, cultural, and social fields and not to be limited to cooperation in the water sector.

To achieve optimal win-win-win policy, the three countries, Ethiopia-Sudan-Egypt should seriously enter into active transparent negotiation, keeping in mind the historical right of Egypt and Sudan and respecting the laws and protocols of the international rivers.

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Erratum to: Impact of the Grand Ethiopian Renaissance Dam (GERD) on Gezira Groundwater, Sudan

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Erratum to:
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Inadvertently, the names of the authors, Hossam H. Elewa, and Alaa M. Kasem were mentioned incorrectly in this chapter. This has now been corrected.

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