Springer Natural Hazards

Mashael Mohammed Al Saud

Flood Control Management for the City and Surroundings of Jeddah, Saudi Arabia

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Mashael Mohammed Al Saud
Space Research Institute
King Abdulaziz City for Science
and Technology (KACST)
Riyadh
Saudi Arabia

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Preface

In different countries around the world, the occurrence of natural hazards has become more frequent and also more widespread in recent years, resulting in severe damage and catastrophic impact on both the environment and on human beings. Several hundreds and in some instances several thousands of people have lost their lives, and affected countries have been compelled to ask for external aid.

The aspects and magnitude of natural hazards differ by region; however, the level of damage is greatest in areas where dense human settlements exist, notably due to lack of strategic planning based on scientific information. Earthquakes and floods are considered to be the most catastrophic natural disasters. These occur as "*flash events*" that take place within a short time period and extend geographically to affect hundreds of thousands of square kilometers in some regions. The impact is greatest in underdeveloped countries and less in developed countries, since in the latter control measures have been implemented that act in reducing or mitigating the damage.

Many natural catastrophic events have taken place in the history of the Arabian Peninsula, and these events have had a very severe impact. The territory of the Kingdom of Saudi Arabia represents the largest part of the Arabian Peninsula, and it has witnessed a recurrence of earthquakes, volcanoes, floods, dust storms, and many types of mass movements, seawater flooding, and many other natural disasters which have caused great damage to humans and the environment. This has been exacerbated by changing climatic conditions and dramatic population growth. In addition, the Saudi Kingdom is a unique Islamic country and many people gather at the holy Islamic sites, especially in the pilgrimage seasons. This influx of people, as well as the importance of conserving the region as a religious centre, makes it even more necessary to implement protective measures against probable natural disasters such as the floods that occurred in Jeddah city and the surrounding area on 25th November 2009 and 26th January 2011.

The damage that has been caused by floods and torrents in the area has demonstrated that the existing protection measures still need to be improved. Before the two flood events of 2009 and 2011, several constructions were already in place to reduce the impact of floods and torrents, such as dams, bridges, and man-made channels, but they did not serve the purpose very well. Also, many urban settlements and roads had been built in valley courses. While urban expansion may have been necessary given the dramatic population growth, it impacts on the occurrence of floods and torrents, indicating that the infrastructure needs to be better planned with such events in mind.

The lack of studies on natural hazards in the Saudi Kingdom compared with studies carried out in other regions, resulted in insufficient knowledge of the natural processes that relate to floods and torrents events, and about how to prepare for these processes. Hence, it is urgent to set up "Early Warning Systems" and to implement the correct controls for protection and for risk reduction. It is essential for researchers and experts to investigate these matters and highlight the key issues, thereby extending the scientific concepts that can be considered by decision makers.

After the first flood disaster in Jeddah in November 2009, several local concerned communities were mobilized, and they immediately sought to extend general awareness of natural hazards and their causes. Consequently, I realized that the factors influencing this type of natural disaster continued to exist, and that there is a need for a rapid and radical solution. Concerned institutions have taken several measures to reduce flood and torrent impact, and thereby conserve human life and the environment. Moreover, the Custodian of the Two Holy Mosques, King Abdullah Bin Abdulaziz, has given this issue special attention, both in terms of identifying the causes of these events and in terms of the measures that can be taken to protect the people.

As a scientific researcher, I realized that it was imperative to undertake the present study, which examines all aspects of this natural phenomenon, including the identification of areas at risk of floods and the proposal of suitable controls that can help in reducing the impact of these disastrous events. For this purpose, I utilized satellite images and geo-information systems as tools for identifying surface features and existing terrain processes, and also for data manipulation. In this respect, processed satellite images with high spatial resolution were of great importance in extracting valuable data and information for the consideration of decision makers.

Now is the crucial time to take the initiative and mobilize all scientific skills and resources, of which there are many in the Saudi Kingdom, and to take action not only to mitigate flood impact, but also in preparation for other natural hazards that may occur in the many regions of the Kingdom.

May God bless my country.

Mashael Mohammed Al Saud

Introduction

Many countries are now concerned about developing environmental issues, notably about the physical changes and increasing number of natural disasters that are taking place on the Earth's surface. The severe damage caused by such disasters means that they require the utmost attention. In response, there has recently been a succession of symposia and meetings pertaining to management approaches toward natural hazards. In the last few decades especially, many regions have experienced this phenomenon, which has been exacerbated by two factors: changing climatic conditions and dramatic population growth, both of which have a mostly negative impact on the environment.

Natural hazards have many aspects and they are characterized by diverse levels of impact between different geographic regions. Some natural hazards such as earthquakes and landslides are flash events, while others such as floods and sandstorms take place over a couple of hours; still others are creeping events that occur over a long time, sometimes over several years; desertification and droughts fall into this category.

Studies of the cause and effect of natural hazards differ in terms of the tools and methodologies applied, which in turn depend on the physical setting of the studied area. Recently, the use of advanced technology has played an integral role in the monitoring and forecast of natural hazards, as well as in identifying the factors that influence their occurrence. The resulting data and information enable the determination of appropriate measures to mitigate and reduce the impact of natural disasters. In particular, space technology and geo-information systems have proved extremely useful in the applied studies being conducted around the globe. As part of this approach, satellite images with various optical and spectral specifications are processed using specialized software in order to obtain digital maps, illustrations, etc. These products are able to identify the areas at risk of natural hazards and deduce the natural setting *before* and *after*. This can be achieved by the manipulation of the influencing factors, which act together to result in natural risk. These factors are integrated in the Geographic Information System (GIS), and then indicative categories to describe risk levels are produced.

After a disastrous natural event has taken place, a risk assessment can be carried out based on the severity of the damages and their geographic distribution. In addition, the mechanism and factors influencing the occurrence can be determined. This will facilitate the proposal of appropriate technical controls to reduce or mitigate the risk.

Motivation

The Kingdom of Saudi Arabia has a long history of natural hazards. It has witnessed not only floods and torrents, but also recurrent seismic activity, sandstorms, sea flooding, volcanic eruptions and mass movements. The chaotic geographic extension of urban settlements, together with climate change, has increased the level of damage that resulted from these occurrences. According to geomorphic and hydrologic characteristics, the western Saudi coast and more specifically the middle part of it, is one of the most hazardous areas in the Arabian Peninsula, and experiences a wide range of natural hazards including mainly floods and torrents. This coastal region encompasses several complicated geomorphologic and structural features (Al Saud 2010a).

The city of Jeddah and the surrounding regions to the east witnessed severe flood events in November 2009 and January 2011 when about 94 and 120 mm of rain fall in a couple of hours; respectively. These resulted in high impact damage to both the human and natural environment, and the inhabitants were in fear after each rainfall period. Since then, many studies have been undertaken to investigate this natural phenomenon. These have employed various procedures and concepts of analysis, and their inducements were also different, but all were targeted toward the proposal of appropriate and effective flood controls in Jeddah and the surrounding areas. The present study applies a comprehensive and integrated approach to the subject matter; physical and anthropogenic factors were analyzed using the latest advanced technology in order to gain a creditable understanding which can be taken into account when making important decisions with regard to flood controls.

Objectives

Prior to embarking on a study such as this, it is of the utmost importance to identify its optimal objectives, and these mainly depend on the previously mentioned motivations. Normally, the objectives will shape the inventory for the items to be studied in order to attain reliable and consolidated results.

The main goal of this study was to understand the flow mechanism of water after torrential rainfall, and thus to identify the areas where water may run or accumulate and assess the impact between running water and urban areas. On the basis of the acquired information, the optimal solutions for draining water along uniform routes, thus protecting both humans and the environment, can be proposed. The objectives of the study can be summarized as follows:

- Identifying the geomorphologic and hydrologic characteristics of the study area with respect to running water on the terrain surface.
- Determining the influencing (natural and anthropogenic) factors in the occurrence of floods and torrents.
- Identifying the areas damaged by the floods of November 2009 and January 2011, as investigated from the processed satellite images.
- Categorizing the damage levels that may result from water and sediments movement in the event of torrential rainfall.
- Mapping flood-prone areas in Jeddah city and the surrounding area.
- Proposing the most appropriate flood controls to reduce and mitigate the impact of floods and torrents.

Contents

Chapter 1
Literature Review and General Concepts

Abstract The region of Jeddah, along the western Saudi coast, has been subjected to severe natural hazards, as evidenced by the two catastrophic flood events that occurred in 2009 and 2011. These floods, which affected the city of Jeddah and the surrounding areas, caused serious and unexpected damage. Yet, studies of this phenomenon are insufficient to provide decision makers with a comprehensive picture of the situation. The following study employed basic scientific approaches and began with a review of the current literature in order to compile an inventory of the principal concepts of the major items to be studied. Thus, the review focuses on the physical and anthropogenic characteristics of the area of study which are of great importance in controlling floods and torrents. In addition, previous studies related to floods and torrents both in the area of concern and worldwide were taken into account.

1.1 The Study Area

Jeddah is located along the middle part of the western coast of the Kingdom of Saudi Arabia, and is described as the "*Bride of the Red Sea*". Jeddah is considered the economic and tourist capital of Saudi Arabia. The city and the surrounding areas have a population of around 3.4 million people, and it is ranked as the second major Saudi city after the capital Riyadh.

Jeddah is the principal route for pilgrims who come from all over the world. For a couple of decades, the center of the urbanized area of the city was located directly adjacent to the coastline, but urban settlement has recently extended to the mountainous regions in the east, and is thus now aligned parallel to the coast on a north-south orientation (Fig. 1.1).

The area was selected for study due to the coincidence between the geography of surface water basins and the fact that it has recently witnessed recurrent floods and torrents, particularly in the area located between Obher in the north and Ar-Ras Al-Aswad in the south. Bounded by mountain chains to the east, it totals an area of about 1947 km^2.

The area of study is located between the following geographic coordinates:

21°56′ and 21°19′N & 39°32′ and 39°06′E

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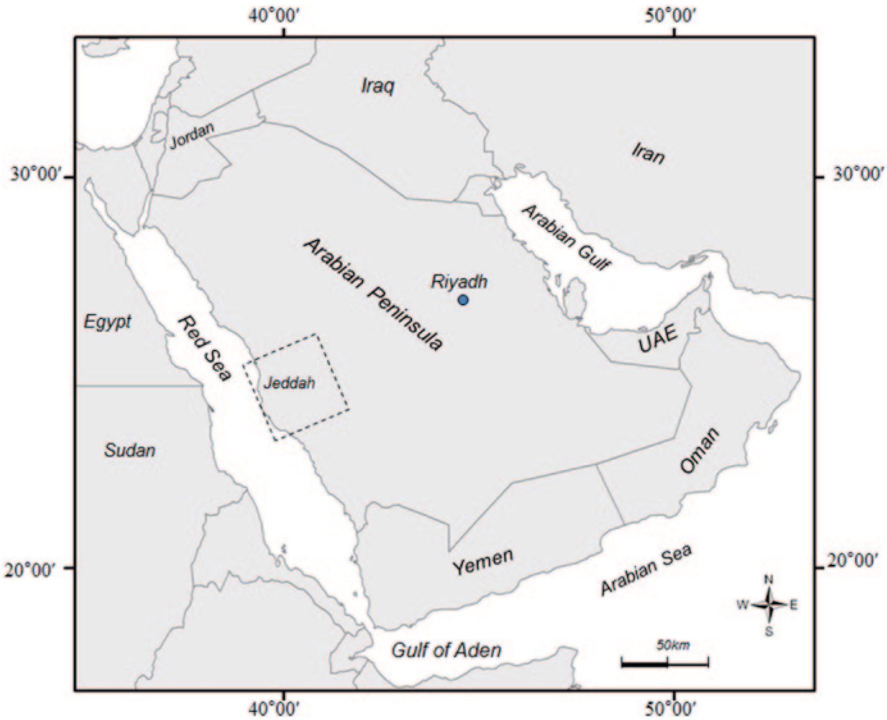

Fig. 1.1 Location map of the study area

The preliminary literature review of available maps and data showed that the geomorphologic and hydrologic characteristics of the area of concern, which has been damaged by floods and torrents in the last few years, were influenced by the urban expansion which has taken place along watercourses (i.e. valleys and channels). The process of urban settlement has closed water pathways or diverted water flow. The blockage or diversion of streams from the mountains from their natural course to the sea has resulted in several human settlements that lay in their path being severely damaged.

1.2 Physical and Anthropogenic Factors Affecting Floods

It is essential to study regions which have been subjected to frequent natural hazards in order to identify the mechanism of occurrence, as well as to assess the magnitude of impact. Identifying the major factors of influence enables us to predict which areas are prone to natural risk, whether in the studied region or in regions with similar physical characteristics, where human interference is also taken into account.

With reference to the floods and torrents that occurred in the Jeddah region during November 2009 and January 2011, it is apparent that the distribution of rainfall was concentrated in defined geographic localities at the time of both events. Moreover, the geographic distribution of the damaged areas and the mechanism of water flow were not similar in both events, according to the diverse physical and anthropogenic factors that played a major role in the occurrence of the floods and torrents. In addition, there are many other regions that have similar characteristics to the study area, and it is thus predicted that these regions will witness similar catastrophic events if torrential rainfall occurs. Consequently, the issue of floods should be a matter of great concern, especially as the entire region of the Arabian Peninsula is subjected to changing climatic conditions. According to the applied global climatic scenarios introduced by IPCC (2007), the Arabian Peninsula is expected to witness an increase in the rainfall rate, accompanied by rainfall peaks (i.e. torrential rainfall) in the next few years.

There are several natural and man-made factors that affect the occurrence of floods and torrents, as well as the resulting damage in different regions. These are dependent mainly on climatic behavior and urban distribution, and also on the property of the terrain which governs the regime and power of the water flow and accompanying processes such as erosion and sedimentation.

The terms ‘flood’ and ‘torrent’ require some elucidation. ‘Flood’ refers to the flow or accumulation of water bodies in places other than those where water naturally flows or accumulates, i.e., in valleys and depressions; while the term ‘Torrent’ refers to torrential rainfall, that is, intensive precipitation, or high energy water flow. Thus, in terms of hydrological concepts, torrents and floods are bodies of water that result from a rapid flow regime due to heavy rainfall accompanied by restricting terrain features (e.g. narrow valley cross-section, steep sloping terrain, etc). The consequent rapid water flow acts to dislodge and set adrift all objects located along watercourses, and thus the water often carries heavy bed loads (e.g. sediments, rock debris, etc). From this point of view, “torrents” often have a more damaging impact than floods.

Normally, rainfall regime is perceived as an essential generating factor in the occurrence of floods and torrents, with focus on rainfall pattern and intensity, which indicate the rate of precipitated water within a limited time period. In cases where precipitation exceeds the infiltration rate, flood water exists on the surface of the terrain. Given this, the factors which are usually considered in assessing floods and torrents can be summarized as follows:

1. Rainfall, including rainfall intensity and pattern.
2. Geomorphologic characteristics of watersheds (e.g. shape, elongation, circularity ration, etc).
3. Morphometric characteristics of streams (e.g. stream order, stream density, stream slope, etc).
4. Geological characteristics (e.g. lithology, rock structures, etc).
5. Soil type and properties.

These factors are often integrated together using conventional approaches to merge different elements that act in flood occurrence in order to determine areas at risk of floods and torrents. The fact that the resultant predictions are erroneous might be attributed to the absence of an influencing factor that may act in controlling the water flow/accumulation regime. Moreover, there are other factors, which have recently been identified by the use of space technology, and shown influence the occurrence of floods and torrents (Al-Saud 2010a, b).

1.3 Previous Studies

Studies on floods and torrents in Jeddah city before 2009 were rare enough, and if they existed, they were merely part of more general studies that focused on broader environmental issues (Al-Saud 2004; Qari 2009). Also, while there were studies dedicated to flood assessment, they were applied to the whole of Saudi Arabia (Nouh 1988; Sorman et al. 1991; Abdulrazzak et al. 1995). In 2009, however, a unique study was carried out that focused on floods that occurred among a number of watersheds in the area located between Jeddah and Yanboua (Subyani et al. 2009).

The topic of floods has been given more attention since the severe episode that took place in November 2009, and especially after another flood occurred in January 2011. Both events resulted in many casualties, and in damage that severely affected the infrastructure and inhabitants of Jeddah City and the surrounding areas (Fig. 1.2).

In the light of these occurrences, investigations were undertaken in order to understand the general conditions that gave rise to them, so that flood control measures could be taken in the region, and a number of preliminary reports and press releases were issued directly after the events. The author of this study is concerned with floods and torrents from the geomorphological and hydrological point of view, and has gathered information obtained using mainly space technology and geo-information systems (Table 1.1).

a b

Fig. 1.2 Examples of flood damage in Jeddah City

Table 1.1 Studies and documents obtained by the author on floods of Jeddah

Delivered to/or published in	Title
Arab Journal for Geo-information System[a]	*Application of geo-information system in floods and torrent assessment in Jeddah 2009*
Geographic Researches Journal[a]	*Mapping floods and torrents in Jeddah city*
Technical Report to Princess of Makkah[a]	*Use of space techniques and GIS in assessing floods of Jeddah 2009*
Technical Report to Princess of Makkah[a]	*Assessing factors influencing floods and torrents in Jeddah using space technology*
Journal of Water Resources and Protection	*Assessment of flood hazards in Jeddah Area 2009*
Chapter in book entitled: "Drainage Systems", published by *InTec*h Publisher	*Use of remote sensing and GIS to analyze drainage systems in flood occurrence, Jeddah—western Saudi coast*
Local and international conferences, seminars and media[a]	A series of lectures and seminars, as well as press releases on floods and torrents of Jeddah and related topics

[a] *In Arabic*

Following the flood events, a number of preliminary preventative measures were taken, but these were not based on solid scientific study of the matter, because such studies did not then exist. There was an urgent need to carry out a comprehensive assessment of the situation in order to avoid the recurrence of such catastrophic events. Many such assessments studies are now taking place, and their results have been noted by various concerned institutions. While they use different tools and methods of analysis, all aim to reach optimal results on the basis of which appropriate flood controls can be implemented.

Since the flood of 2009, the author has been following up the actions taken with regard to floods in Jeddah City and its surroundings, and has started to investigate the major elements of the issue using credible and advanced scientific procedures. The author aims to provide decision makers with the most reliable facts and findings, as well as to publish the results in peer-reviewed scientific journals and bulletins in order to support the creditability of the work (Table 1.1).

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Chapter 2
Methodology and Tools of Analysis

Abstract Several methods are used for flood risk assessment. These differ between regions and even between investigators depending on the tools that are available for data analysis. Recently, remotely sensed data have become a useful source of information with regard to terrain characteristics and water flow regime. The use of different spatial and temporal resolution satellite images and digital elevation models (DEMs) is essential for data manipulation in the GIS system, with a special emphasis on flood risk assessment and mapping of the flood-prone area.

2.1 Methodology

Several methodologies are applied to the study and assessment of floods and torrents, which usually produce diverse results according to the procedures of analysis that are applied to identify areas at risk from natural hazards. However, new advanced techniques have a major role to play in this respect, since these techniques have become a useful tool for monitoring and identification purposes, as well as for damage assessment.

Some established procedures are applied directly in the field (i.e. *in-situ* measurement) and others observe the surface of the terrain from space. The use of new techniques is mainly dependent on their availability as investigative tools. Due to the fact that flood water follows spatial distribution on the terrain surface, maps and satellite images are useful tools for analysis.

In order to achieve an optimal study with creditable results, it is first necessary to identify the major objective of the study. This is because the study of floods and torrents may have different purposes in different regions; consequently, tools and procedures may differ also. In addition, some studies focus on only one theme related to floods, such as analyzing the geomorphologic aspects (Subyani 2009); or establishing digital models (KACST 2011), or drainage morphometric analysis (Yehia and El-Ater 1997), while other studies treat all concepts related to the flood process (Al Saud 2010).

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Table 2.1 Used satellite images in this study and their major specifications

Satellite	Spatial resolution (m)	No. of bands	Acquiring date	Utility
Ikonos	1	5	10/10/2009, 30/11/2009, 19/2/2010	Comparison before and after floods
				Identifying damaged areas by flood (2009)
Worldview-1	0.5	8	27/1/2011, 1/3/2011	Identifying damaged areas by flood (2011)
Worldview-2	0.5	8	8/2/2011	Overlapping spatial data
Quick Bird	0.5	5	2/3/2011	High precision comparative analysis for recognized small-scale flooded areas
Geo-eye 1	0.5	5	2010	Establishing DEM aspects
Aster	15	14	2009	Identification of geological features

The major areas of investigation in studying floods and torrents can be summarized as follows:

1. Mapping flood-prone areas.
2. Identifying factors that influence floods and torrents.
3. Assessing the damage caused to areas by floods and torrents.
4. Studying and proposing flood controls for better flood mitigation.

Bearing in mind these areas of investigation, the appropriate methodology can be decided upon, and after identifying the physical and anthropogenic factors that are at work, flood controls can be proposed based on scientific understanding. The listed areas of investigation that comprise the basis of the study may be compared with the studies that have been undertaken on floods in Saudi Arabia. However, there is no similarity between the two, except the studies done by the author, as revealed in Table 2.1. The present study will integrate the listed areas of investigation within a comprehensive theme of analysis. In addition, the natural factors which exist in the study area and the assessment of the two flood events that occurred in 2009 and 2011 will be examined. This study was completed in two phases and over approximately 2 years (Fig. 2.1). The first phase was started directly after the catastrophic flood event of November 2009, which resulted in severe damage to the east and south-east of Jeddah City over an area totaling about 688 km^2. A comprehensive assessment was carried out, after which the acting factors were identified. For this, satellite images were used, which were analyzed in accordance with different thematic maps.

After the flood event which occurred in January 2011, and which mainly affected the north-east and northern areas of Jeddah City, as well as extending to some southern regions, the second phase of study was started, and it had a larger spatial coverage. The geography of the new area (of the second phase) was increased to about 1947 km^2.

The methodology followed in this study was achieved by an ordering scheme, and consisted of a number of practical tasks. This methodology depends, in a broad

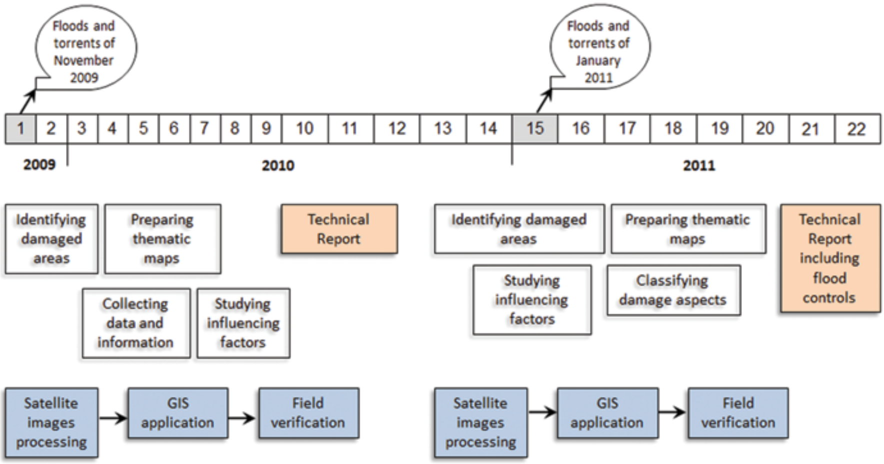

Fig. 2.1 Flow chart of the major phases of the study

sense, on preparing data and information on the area of concern, and then correlating these data and information with other analyses of floods and torrents which have focused on different aspects. Hence, these two components will help in identifying the factors governing floods and torrents in Jeddah and its surroundings. Based on the results, flood controls can be proposed to mitigate the impact of these catastrophic events. Also, determining the influencing factors helped in selecting the proper methodologies for this study, which enabled decision makers to take appropriate action.

2.2 Tools for Analysis

It is necessary to have all tools for analysis prepared before starting such a study, since the proposed methodologies in many studies fundamentally depend on the availability of the tools that are required. Normally, different tools and applications are used even for one theme. They can include desk study documentation and laboratory investigation, while other applications require field surveillance and *in-situ* measuring. All of these aspects depend on the topic to be investigated and its objectives.

Floods and torrents are studied from different spatial aspects. This can be mainly achieved by studying their geographic distribution and monitoring the water flow regime, as well as by identifying the physical and anthropogenic factors that influence them and other related elements. This enables the coverage of large geographic areas of surface terrain. Hence, it is of the utmost importance to focus on the use of spatial tools for analysis. These are mainly represented by maps, aerial photos and satellite images, in addition to other supplementary tools, such as time series records, data and other related research aspects.

The sections below show the principal data and tools used in this study.

2.2.1 Data and Supplementary Information

- Climatic records from ground stations to investigate rainfall peaks by region.
- Climatic records from remotely sensed data to cover the lack of ground data.
- Terrestrial thematic measures (e.g. damaged areas, channel characteristics, lake capacity, existing flood controls, etc.).
- Supplementary information, including historical flood events, urban expansion and instigated protection.

2.2.2 Maps

- Topographic maps (1:50.000 scale& 20 m contour interval)
- Geological maps (1:250.000 scale & 1:500.000)

2.2.3 Digital Elevation Models (DEMs)

- Digital Elevation Model, DEM of 2 m accuracy[1].
- Digital Elevation Model, DEM of 30 m accuracy.

2.2.4 Satellite Images

In this study, satellite images with different optical and spectral characteristics were processed. They encompass various technical specifications, such as images of the scene area (i.e. swath width), re-visit time, number of bands, etc. In addition, these images were acquired close to the date of flood occurrence (Table 2.1).

2.2.5 Software

- ENVI-4.3 for satellite image processing (produced by: IBM. Colorado, USA).
- ERDAS Imagine-9.3 for satellite image processing (produced by: Lucia, Georgia, USA).
- Arc-GIS-9.3 for Geographic Information System applications (produced by: ESRI, Redlands, USA).

[1] Space Research Institute, King Abdulaziz City for Science, Saudi Arabia.

2.3 Satellite Image Processing

Space science has become an extremely useful tool for analysis in many geo-spatial applications, notably in those related to the study of surface terrain and the processes that take place on it. Space science is mainly comprised of the study of digital satellite images. These images enable the identification of terrain features which are associated with natural hazards. The efficiency of these satellite images has been clearly demonstrated, especially in the assessment and study of floods and torrents, which are characterized by different optical and spectral specifications that enable the identification of flood processes. Satellite images have a miscellany of properties, and it is essential to consider these when selecting the type of satellite image to be analyzed. For instance, it is important to consider the "Spatial Resolution" of the image, which reflects its capacity to identify terrain features from space. For example, from space, Ikonos images can recognize objects on the Earth's surface of approximately 1 m × 1 m area. This is virtually equal to an observation from space of about 100 m altitude; whilst MODIS images cannot discriminate objects on the Earth's surface with an area less than 250 m × 250 m. In addition, there is another property which must be considered when selecting a satellite image: the "Re-visit time", which represents the time that a satellite needs to return to the same location above the Earth's surface. For example, the Landsat satellite takes 16 days to complete one orbit around the Earth, while the SPOT satellite takes 26 days.

Moreover, satellite images of various types have many electronic properties, such as the number of bands and their wavelength and spectrum ranges (e.g. thermal band, optical band, etc). After considering these properties, a number of satellite images were selected for this study. The Space Research Institute at King Abdulaziz City for Science and Technology (KACST), in Riyadh played a major role in providing many of these images. Thereafter, six different satellite images were processed using the above ENVI-4.3 and ERDAS Imagine-9.3 software (Table 2.1 and Fig. 2.2). These images were acquired at different dates, and they cover different terrain localities within the area of study.

One of the great advantages of the selected satellite images is the dates on which they were acquired; some of them were retrieved before the date of the two flood events, and some others directly after these events. In addition, each of these images was composed of a number of scenes in order to cover the largest spatial area of the damaged terrain. Overlapping between different satellite images was applied to cover the entire region of Jeddah City and its surroundings (Fig. 2.2).

Usually, a variety of spectral analysis approaches for digital image processing is applied to facilitate the recognition of objects that appear on the terrain surface, and then different analyses and measures are required. For example, in ERSAD Imagine software, the most useful applied digital steps are directional filtering, in addition to contrasting and sharpness. Band combination is also applied, where single band and multi band enhancement are carried out by interrelating each three bands as

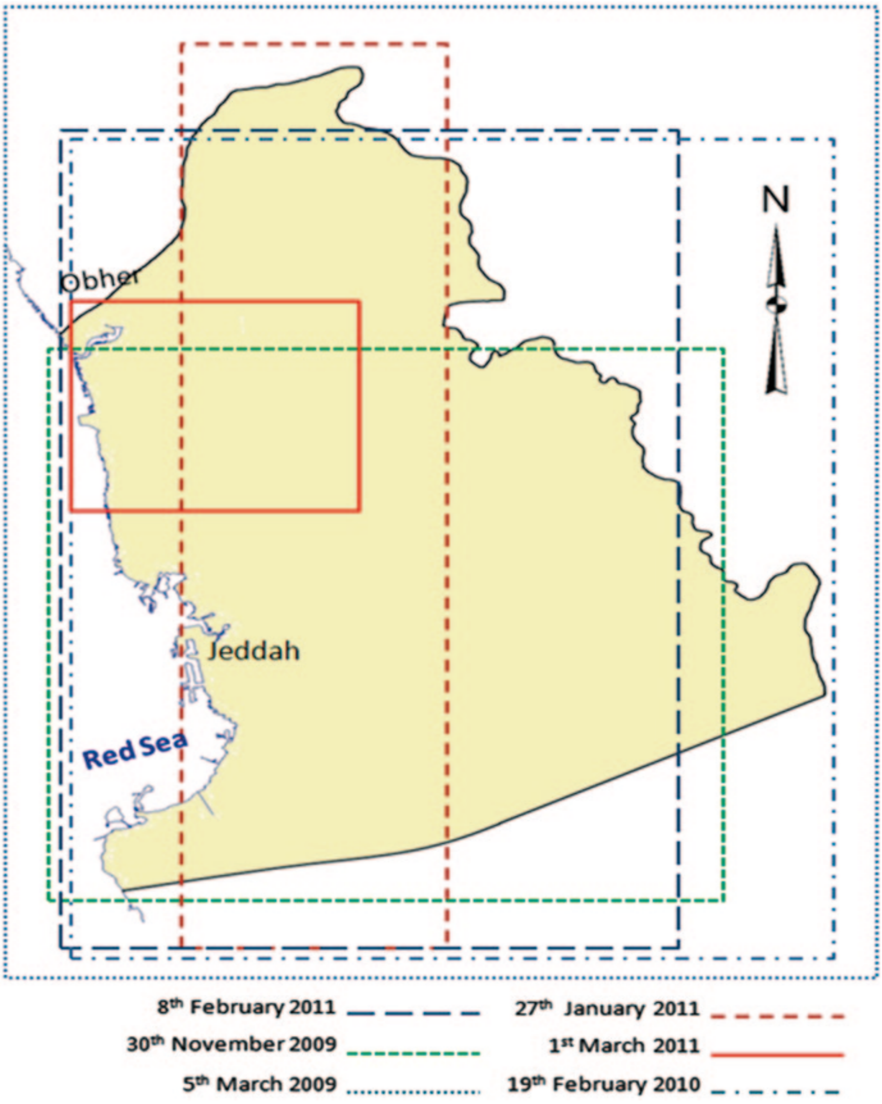

Fig. 2.2 Satellite images used in the study

one set. These applications are helpful in detecting color differentiation, as well as pattern and tone, which facilitates the recognition of terrain features. Moreover, the recognition of temperature difference for various objects from thermal bands is a very useful application. ENVI-4.3 software is also good for processing digital satellite images. It includes the following digital applications: enhancement, interactive stretching, density slicing, coloring and spectral analysis (Fig. 2.3).

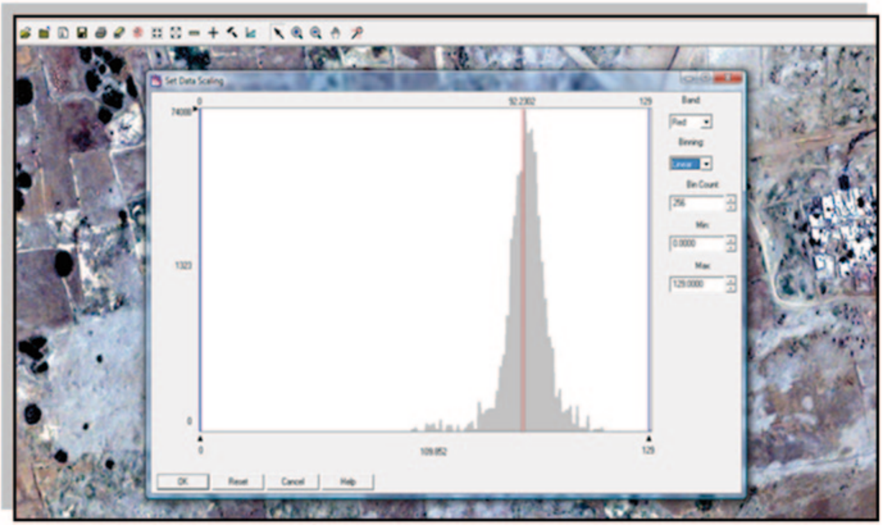

Fig. 2.3 Example of spectral analysis application on image processing

2.4 Geographic Information System (GIS)

The applications of GIS are different from those in image processing. GIS serves in data analysis and modeling, as well as in data storage and manipulation, while image processing of satellite images is used as a tool to extract geo-spatial data observed on the terrain surface. Thus, the use of GIS in studying natural hazards implies a systematic integration with space science. The application of GIS also involves mapping approaches, which are digitally implemented, in addition to data harmonization for further manipulation between different sets of databases, and this facilitates the reading of geo-spatial information.

In the assessment of floods and torrents, GIS is integrally supported by the geomorphologic and hydrological information that has been extracted. Therefore, different variables and statistics can be measured and analyzed, notably when it is applied to diagnosing drainage systems, whether for the geometry of the basin or the streams within each basin. This is essential for identifying the mechanism of the flood process, in terms of the running water or water accumulation on the terrain surface.

Arc-GIS software is able to generate all thematic information together and reveal the required database and maps on the same board. Therefore, data integration can be applied in systematic selection built on digital approaches whenever it is needed (Fig. 2.4). This helps in identifying geographic zones which require further investigation and consequently calculating different measures and dimensions.

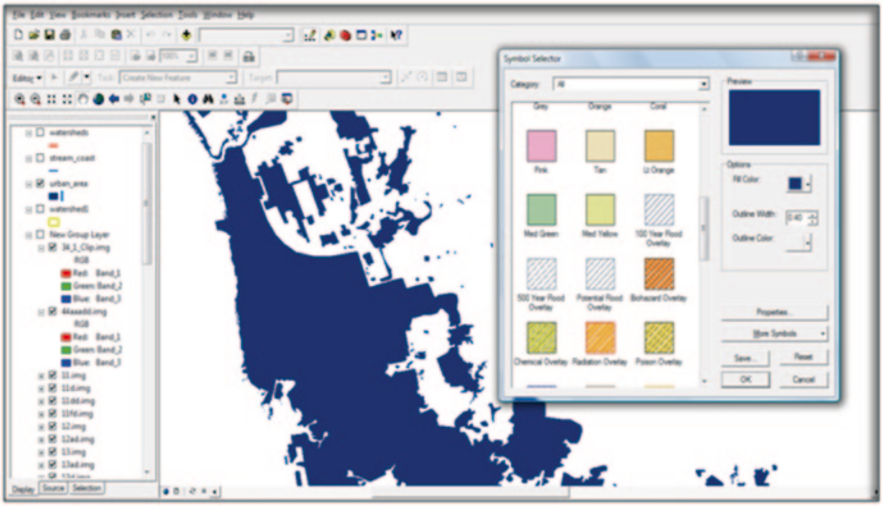

Fig. 2.4 Example showing the integration of different database in Arc-GIS

2.5 Digital Elevation Models (DEMs)

Geographic information systems (GIS) can be used to build three-dimensional models for any geographic location on the Earth's surface. The presentation of terrain topography for any site needs data from three-dimensional variables (z, y, x), which is known as the Digital Elevation Model (DEM). The buildup of DEM is well pronounced in several applications, such as identifying slopes, run-off, sunlight exposure, drainage systems, low-lands, etc. It also has widespread geomorphologic and hydrological applications, especially since this technique allows the identification of topographic features with their morphometric behavior.

The concept behind establishing DEMs implies the treatment of terrain elevation points whether from digital contour lines or from stereoscopic satellite images (e.g. SPOT images). Hence, the "triangulated irregulated network" (TIN) must be firstly constructed (Fig. 2.5). This represents digital data structure used in the GIS

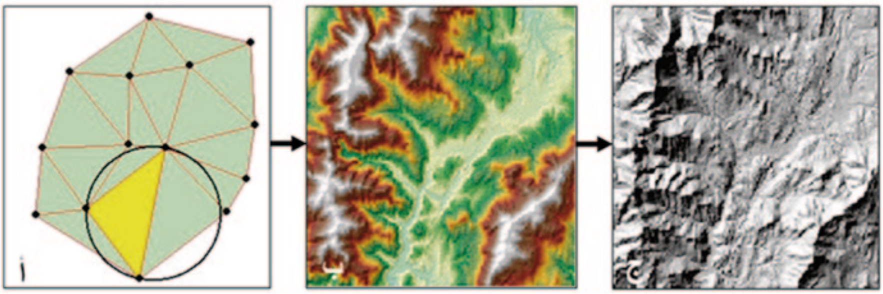

Fig. 2.5 Example on the "triangulated irregulated network" (TIN) approach to build three-dimensional models

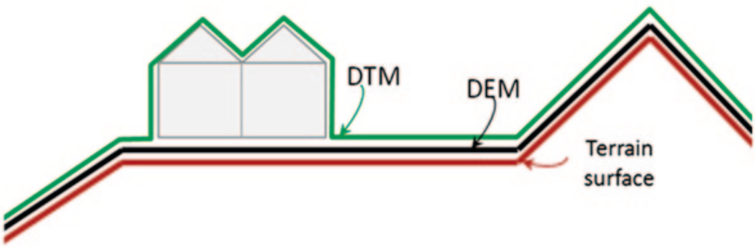

Fig. 2.6 Example showing DEM and DTM

system of surface attributes for the physical characteristics of land surface, made up of irregularly distributed nodes and lines with three dimensional coordinates that are arranged in a network of non-overlapping triangles. DEM extraction can also be obtained from digital data for elevation attributes. Therefore, digital contour lines on digital topographic maps are useful for establishing DEMs.

Three-Dimensional (3-D) models differ according to the purpose of the study. They can be Digital Elevation Model (DEM) or Digital Terrain Model (DTM). In the first, the 3-D shows only the elevations of terrain surface level, while DTM shows all elevations on the terrain surface including human settlements and construction sites (Fig. 2.6).

In this study, two approaches to build DEMs were followed. The first was from digital topographic maps with a contour interval of 20 m, after applying a systematic digitizing procedure for these contours. The second approach uses the Geo-eye-1 satellite with a 2 m contour interval, which was provided by the Space Research Institute at King Abdulaziz City for Science, in Riyadh. These images are characterized by stereoscopic viewing (acquiring visualization from two facing sides on the satellite). This visualization enables the extraction of the elevation in digital forms, and thus it is used in constructing DEMs for further hydrologic and geomorphologic analysis, which was applied to draw watersheds in Jeddah and the surrounding area.

2.6 Field Verification

Field verification includes carrying out a survey of the terrain in order to confirm the reliability of information and data extracted from satellite images, as well as to assess the accuracy of information derived from the obtained thematic maps, which were resulted from the integration of different digital geo-spatial themes. Field verification was carried out in phases, notably after the flooding events in 2009 and 2011.

Topographic maps (scale 1:50.000) and satellite images with several optical and spectral characteristics, notably high-resolution ones, were used in the field verification. Field notes, modifications and corrections, as well as other related information were reported for each site after measuring the geographic coordinates using the Global Positioning System (GPS).

The main objective of field verification is the assessment of the geographic distribution of flood zones, and thus these zones were measured in terms of water depth and erosion rate, for example. In addition, different aspects of the damage were investigated, including its dimensions and spatial distribution. In this way, field verification enables the identification of all physical and anthropogenic factors that influence floods and torrents. It also helped in recognizing the historical and socio-economical aspects that affect floods and torrents, as they were declared by the inhabitants, and facilitated recognition of the small-scale flood controls that were put into place by the inhabitants of the area.

In addition, a detailed field reconnaissance was carried out in the localities where flood controls exist, such as water channels, tunnels, bridges, as well as the old and new reservoirs, i.e. El-Mesek Lake (formerly named), the Precautionary Dam, Es-Samer Dam and Omm El-Kheir Dam. Other protective measures that were carried out after the floods and torrents of 2009 and 2011 were also investigated. Based on field verification, new flood controls were proposed by the study.

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Chapter 3
Physical and Anthropogenic Factors

Abstract Natural hazards are controlled by many physical and anthropogenic factors that govern the level of risk and its geographic distribution. These factors vary between regions and are not well defined; different studies have produced contradictory findings. The present study investigated the fundamental factors that influence floods and torrents in Jeddah city and the surrounding area, based on the flood events that took place in 2009 and 2011.

3.1 Drainage Systems

Recently, new electronic and geo-information techniques have been used to delineate surface water routes (i.e. streams), and thus also catchment areas (i.e. watersheds or basins). This application is very useful in remote and rugged areas, notably in those which are not topographically mapped. In these cases remotely sensed data are used which mainly depend on acquiring elevation points on the terrain surface, which must be acquired digitally. In this respect, Digital Elevation Models (DEMs) can be applied as a useful tool for building drainage systems.

By using these techniques the flow direction of surface water and the location of lowlands can be accurately induced. In addition, they help in identifying the behavior of topographic surfaces. In this regard, DEMs play a major role in tracing drainage pathways, notably in the coastal zones where these paths are virtually hidden due to intensive sedimentation processes, in which case they do not appear on topographic maps. This facility is also helpful in tracing stream courses in urban areas and in areas with uncovered geomorphological shapes, as is the case in Jeddah City.

However, it is common for established DEMs to make errors in this regard, i.e. the streams do not actually exist on the terrain surface, and they do not coincide with geomorphologic and hydrologic concepts. Such errors may be due to the following reasons:

- The existence of complicated topography, notably in the local steep sloping terrains as well as in the cliffy sites, which result in distortion in drawing the vertical dimensions. This is well pronounced in the elevated and mountainous regions close to Jeddah City, especially where igneous and metamorphic rocks exist with sharp and rugged exposures.

M. M. Al Saud, *Flood Control Management for the City and Surroundings of Jeddah, Saudi Arabia,* Springer Natural Hazards, DOI 10.1007/978-94-017-9661-3_3

- The resulting distortion in the satellite images due to the pre-processing procedures (e.g. geometric and atmospheric corrections, etc), even though the processed satellite images are characterized by the property of high resolution.

However, there are a number of electronic applications, which give accurate geo-spatial results. These applications are used to recognize digitally the flow regime in different water tributaries, where the precision reaches tens of centimeters. Such is the case when using LIDAR systems, which are able to build precise DEMs. However, these systems sometimes entail vertical distortion due to steep slopes and cliffs which results in shaded zones and thus terrain features are shown that do not in fact exist.

In this respect, many researchers agree that the new geo-spatial techniques need to be further developed for better accuracy (e.g. Mark 1983; O'Callagham and Mark 1984; Jenson and Domingue 1988; Tribe 1991; Ichoku et al. 1996; Martinez-Casasnovas and Stuiver 1998). When this is attained, they may be of great help in drawing procedures.

The drawing of drainage systems often entails the direct digital tracing of streams from topographic maps, as was the case in this study, where topographic maps with 1:50,000 scale and 20 m contour interval were utilized. These maps were previously obtained by the stereoscopic analysis of aerial photos, and in some instances they also showed errors in the tracing of streams. These errors can be easily identified, since they are not in line with geomorphic concepts. Therefore, many drawing errors on topographic maps were treated in this study.

In this study, the DEMs data, which represents elevation nodes, were projected on to the digital data derived from topographic maps. This reduced the possibility of error, as well as utilizing the benefits of both data sources (i.e. DEMs and topographic maps). Consequently, drainage system maps were obtained electronically for all hydrologic elements. Data from these maps was stored digitally in Arc-GIS 9.3 software. This facilitates manipulating digital data, as well as applying different treatments, and thus calculating the required measurements which can be stored on a database.

Satellite images were also utilized to establish the existence of drainage systems. In this respect, Aster images were useful, notably because they include five thermal bands. Hence, depending on the recognition of moisture content, Aster images helped in detecting non-exposed stream channels, which do not appear on topographic maps.

When that was achieved, the digital maps which showed the existing streams and reaches were used to illustrate water divides and to classify the area into different watersheds (i.e. catchments). The extension of watersheds in the coastal zone was almost controlled with the existing man-made channels, which are described locally as "Storm Channels". This created some discrepancy between the watershed areas determined in this study and those that were determined in previous studies obtained by the author. Therefore, watersheds in the city of Jeddah were completely drawn. They include the entire region located between Obher in the north and Ar-Ras Al-Aswad in the south, and extend to the mountain chains to the east of Jeddah city. This comprises a total area of about 1947 km^2.

Accordingly, the watersheds in the area of concern were divided into three basin types, namely the major, minor and joining watersheds (Fig. 3.1 and Table 3.1), which can be described as follows:

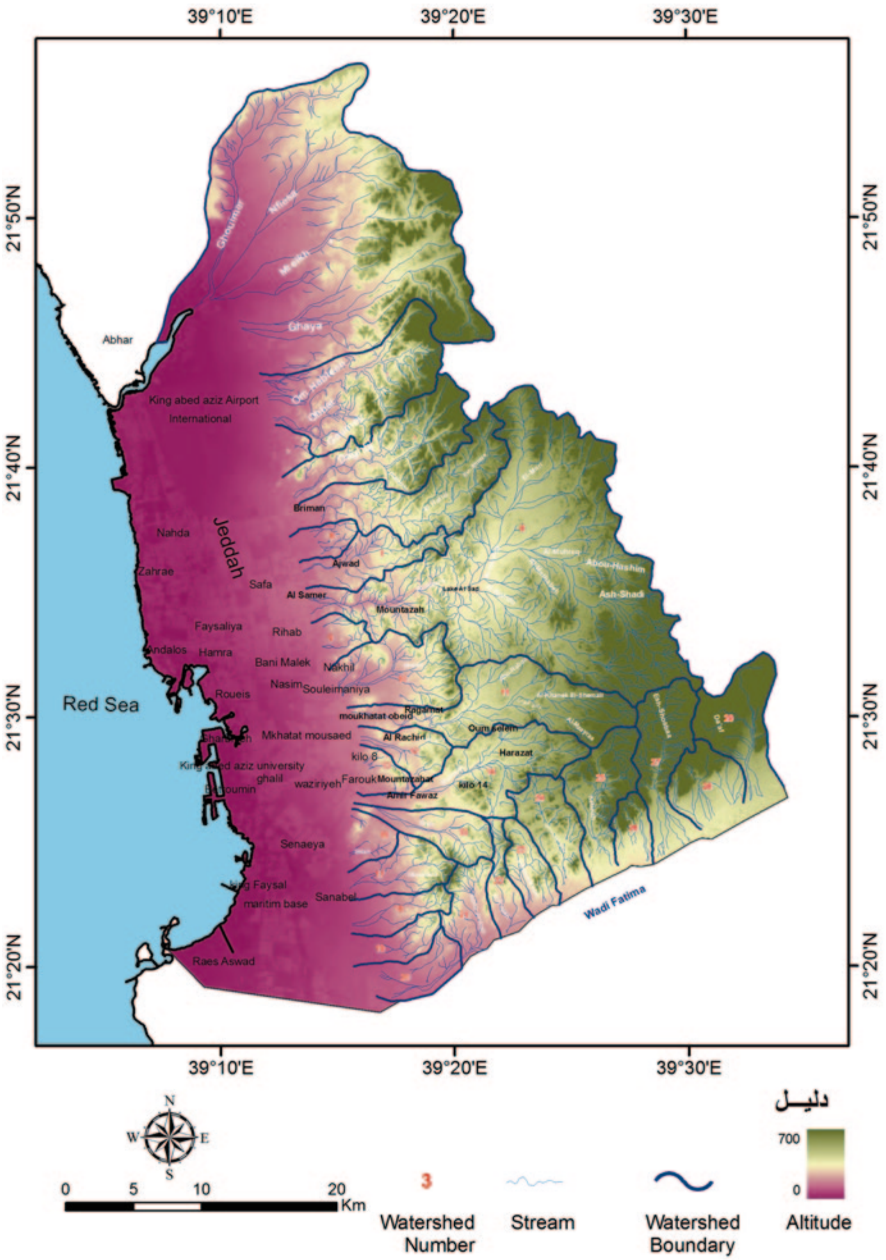

Fig. 3.1 Basins in the study area

Table 3.1 Basins and their streams in the study area

No.	Watershed	Area (Km^2)	Type				Connected valleys
			Number	Major	Minor	Joining	Stream name
1	Ghouiemer	319.7	4	x			Ghaya, Mreikh, Nfiesa, Ghouimer
2	Om Hableen	75.7	2	x			Obhar, Om Hableen
3	Basin # 3	6.5	–			x	Incomplete basin
4	Daghbj	56.9	2	x			Daghbj, El-Melahi
5	El Hatiel	59.6	2	x			El Hatiel, Esh-Shraya
6	Basin # 6	10.3	–			x	Incomplete basin
7	Basin # 7	25.8	–		x		One major tributary connected other tributaries
8	El Assla	289.4	8	x			El-Mari, Abou-Hashim, Al-Muhreq, Ash-Shadi, Al-Mathabeh, Al-Houfna, Al-Ramda, Al-Assla
9	Basin # 9	10.4	–			x	Incomplete basin
10	Mreikh	46.7	–		x		One major tributary connected other tributaries
11	Kawes	70.1	4	x			Abo-Nabaa, Al-Khanek El-Shemali, Al-Mzayraa, Kawes
12	Osheer	17.7	–		x		One major tributary connected other tributaries
13	Basin # 13	12.5	–			x	Incomplete basin
14	Methweb	54.2	–	x			One major tributary connected other tributaries
15	Ghlil	23.1	–		x		
16	Selsli	13.7	–			x	Incomplete basin
17	Muwaieha	23.7	–		x		One major tributary connected other tributaries
18	Basin # 18	17.6	–			x	Incomplete basin
19	Basin # 19	14.8	–		x		One major tributary connected other tributaries
20	Basin # 20	21.6	–			x	Incomplete basin

Table 3.1 (continued)

No.	Watershed	Area (Km^2)	Type				Connected valleys
			Number	Major	Minor	Joining	Stream name
21	Abou Je'Alah	21.2	–		x		One major tributary connected other tributaries
22	Al A'ayah	14.7	–		x		
23	Ed-Dowikhlah	17.1	–		x		
24	El-Baghdadi	29.6	–		x		
25	Ketanah	34.7	–	x			
26	Basin # 26	13.0	–			x	Incomplete basin
27	Esh-Shoabaa	40.5	–	x			One major tributary connected other tributaries
28	Basin # 28	24.4	–			x	
29	Da'af	37.9	–	x			

Basins with names are according to the topographic maps
Basins with numbers have no specific name

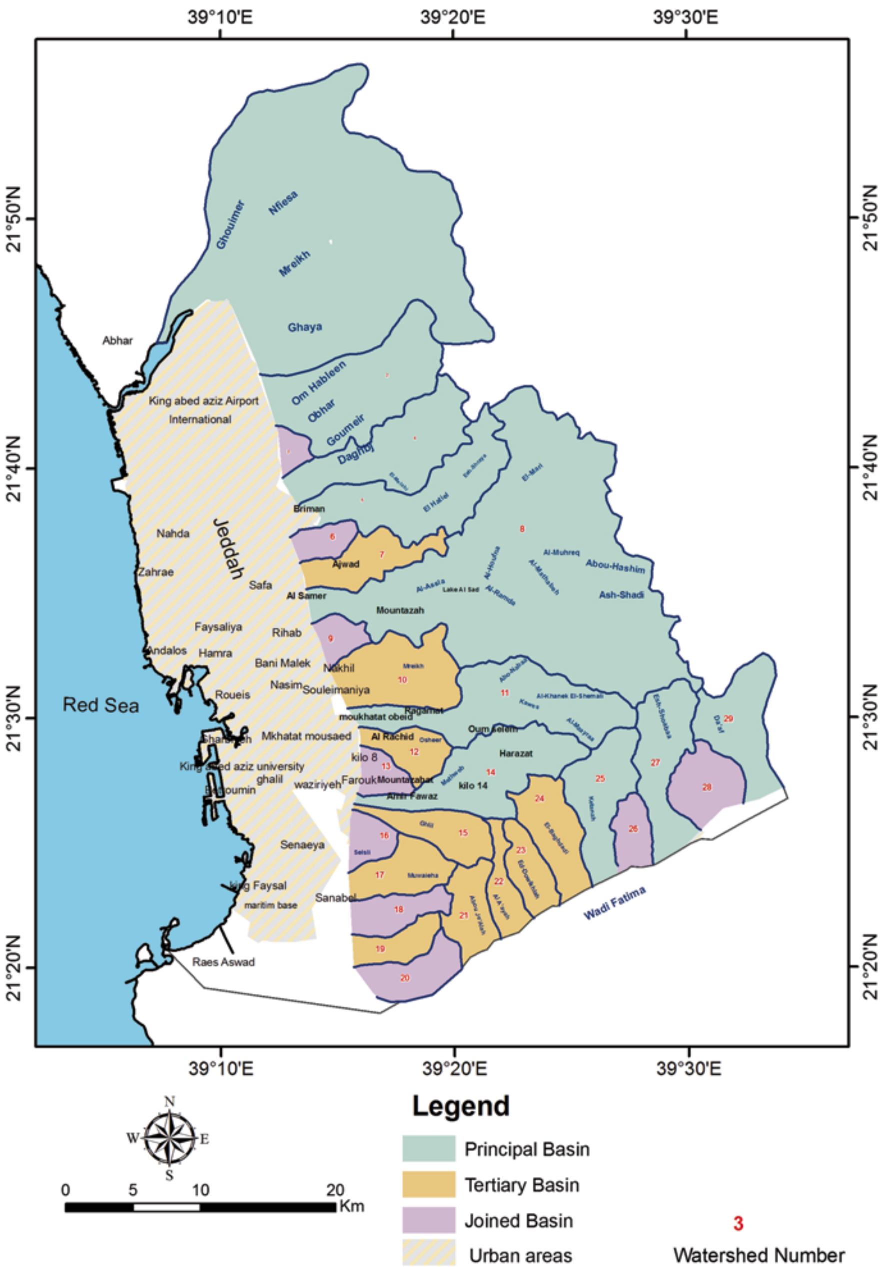

Fig. 3.2 Classified basin types in the study area

1. Major basin: This term describes a basins with normal hydrological characteristics, such as funnel or semi funnel geometry (Fig. 3.2), where the ration between the numbers of branches is higher in the upstream than in the down-

stream area (Fig. 3.1). It is also characterized by uniform run-off among ordinary stream connections. There are 10 major basins in the study area. These are basins number 1, 2, 4, 5, 8, 11, 14, 25, 27 and 29 (Fig. 3.2).
2. Minor basin: This term describes basins that are smaller in terms of area than major basins (often less than 50 km^2), and they usually have non-uniform run-off (Fig. 3.1). There are ten minor basins in the study area. These are basins number 7, 10, 12, 15, 17, 19, 21, 22, 23 and 24 (Fig. 3.2).
3. Joining basin: This term denotes incomplete basins, which occupy the geographic extension between the major and minor basins, and which are not controlled by a defined flow regime. They also do not have one well-defined outlet (Fig. 3.1), but rather a number of outlets which are sometimes buried due to the eroded alluvial deposits. There are nine joining basins in the study area. These are basins number 3, 6, 9, 13, 16, 18, 20, 26, and 28 (Fig. 3.2).

The area of concern occupies 29 basins: 19 of them outlet directly towards the coastal zone to the west and have a total area of 1170 km^2; the remaining ten basins outlet towards Wadi Fatima to the south and have a total area of 233 km^2 (Table 3.1).

In the study area, Wadi Ghouiemer and Wadi El-Assla are the largest basins in terms of area, and they cover about 319.7 km^2 and 289.4 km^2; respectively. However, it is evident from Fig. 3.1 that the geomorphologic features of many basins have been obscured due to urban development.

3.2 Rainfall Distribution

Over the last four decades, there have been changes of the rainfall rate and pattern in Jeddah city and the surrounding areas to the east. Three decades ago, the average rainfall rate was recorded at between 350 and 400 mm (Italconsult 1967); however, recently it has fallen into the range of about 60 mm according to the General Corporation for Forecasting and Environmental Protection (GCFEP)[1]. The run-off rate was estimated at between 5 and 6% (Es-Saeed et al. 2004). The cloud masses are often formed in the spring with some torrential rainfall peaks in November. In addition, rainfall increases during the evening and is accompanied by relatively dense cloud and strong westerly winds.

The decrease in rainfall rate (approximately five times) over the last three decades is accompanied by a clear frequency of rainfall peaks: heavy rainfall over a short period of time, thus indicating changing climatic conditions. However, it is anticipated that there will be an increase in the rainfall rate of about 30% over the next few years in the Arabian Peninsula region (IPCC 2007). Also, climatic scenarios indicate that the increase in rainfall will be dramatic and affect all arid regions. An increase in temperature accompanied by a decrease in rainfall in the humid regions to the north of the Peninsula is also predicted.

[1] Daily records from GCFEP.

Given the lack of gauging stations in the area of study, it was necessary to employ space technology to fill the gaps that exist in the rainfall records, and by these means identify the geographic distribution of rain and torrents that occurred in Jeddah City and the surrounding area in 2009 and 2011, which could not otherwise be accurately determined.

To this end, a continuous precipitation record was adopted from a remotely sensed data system entitled "Tropical Rainfall Mapping Mission" (TRMM)[2], which is a space system that largely depends on acquired radar data. It is extended as a joint enterprise between NASA and the Japan Aerospace Exploration Agency (JAXA). This system was primarily designed to study and monitor tropical rainfall. Data in this system is acquired on a global and daily basis. It can be retrieved either as graphic illustrations or as contour maps for any selected area and time interval.

The coordinates of the study area were plotted on the TRMM system. They cover the area between Obher to the north and Ar-Ras Al-Aswad to the south, and thus extend from the coastline to the mountain chains in the east. The selected time interval was limited to the date of the two flood events (2009 and 2011). Subsequently, rainfall intensity and distribution were retrieved from the TRMM system for the study area (Fig. 3.3).

It was clear that the cluster rainfall masses of 25th November 2009 were mostly located over the mountainous regions to the east of Jeddah City (Fig. 3.3, zone A), in addition to many other dissipated clusters of rainfall masses of less density located in the coastal zone (Fig. 3.3). It was also evident that the main rainfall mass (zone A) encompassed a diameter of about 90 km, and this is virtually consistent with the measurement which was previously proposed by the author (Al-Saud 2010c). Accordingly, the resulting damage map for the floods and torrents of November 2009 shows that the damage mainly occurred in the mountainous region, which is coincident with the location of the rainfall masses observed using the TRMM system, as in Fig. 3.3.

The rainfall rate that was witnessed on 25th November 2009 was estimated at 95 mm over a couple of hours as demonstrated by GCFEP. This rate exceeds by approximately 55 % the average recorded rainfall rate (i.e. 60 mm) in the studied region. This shows the importance of rainfall as a generating factor of floods and torrents. According to the rainfall rate recorded on 25th November 2009, it is predicted that any increase above this rate may result in a condition of risk in the area of study if proper measures are not implemented.

In respect of the floods and torrents that occurred on 26th January 2011, as shown in the TRMM system (Fig. 3.3), dense clusters of rainfall masses were found in two zones (i.e. C and D). The first of these was in the northern part of the study area adjacent to Obher city, and the second was in the south facing Jeddah city. They appear to have a smaller geographic area and less density than those that occurred in 2009. This is directly proportional to the geographic distribution of the areas that were damaged in January 2011 (according to GCFEP), which had less impact even though 120 mm rainfall was reported over the course of 26th January 2011.

[2] http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42.2.shtml.

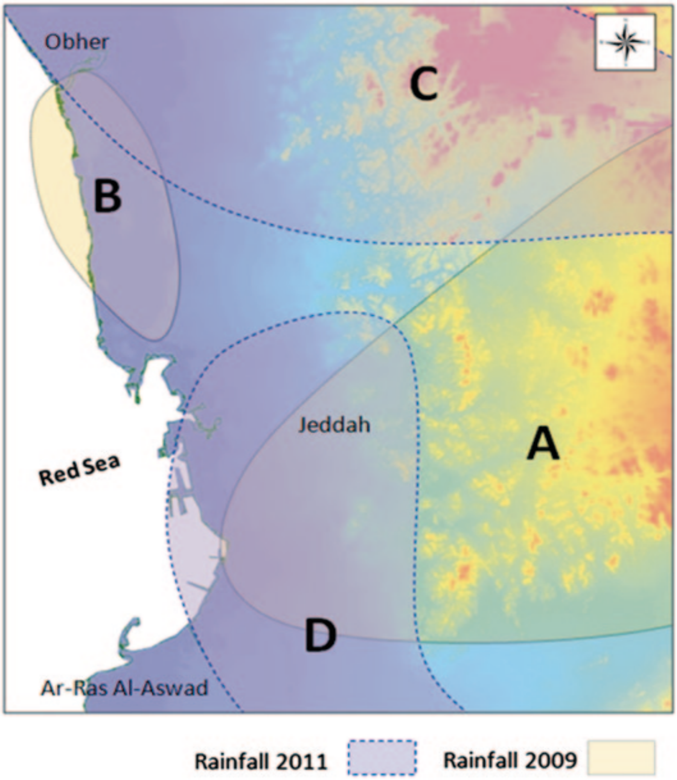

Fig. 3.3 Rainfall distribution (25th November, 2009 & 26th January, 2011) according to TRMM

3.3 Geomorphologic and Geologic Characteristics

Geomorphologic and geologic characteristics play a major role in controlling the mechanism of occurrence of floods and torrents. This shows the importance of identifying primarily these characteristics for any area to be studied in this respect. For example, the characteristics of flow energy of floods and torrents, as well as their distribution, differ between mountainous and low-land areas. Slope gradient also plays a role, in addition to rock characteristics including their hardness and fracturing systems, in which regard they have an influence on surface run-off and infiltration rates.

3.3.1 Geomorphology

Aspects of terrain morphology and the influence of physical features on it represent the geomorphology of the Earth's surface. These aspects significantly affect surface water flow, notably after torrential rainfall events. The principal geomorphologic aspects that control flooding in the study area can be diagnosed as follows:

3.3.1.1 Geomorphologic Shape

Normally, the general geomorphologic shape of any region is viewed comprehensively so as to observe all terrain elements together and thus identify the general setting and interrelation of terrain components, notably those controlling floods and torrents.

In this study, the general geomorphologic shape of the area was induced from satellite images through the application of projections on DEMs in order to observe the area of interest in three-dimensions (3-D) (Fig. 3.4). The resulting 3-D shape shows a general overview of the area. It clearly shows the existence of two principal regional basins, as follows:

1. The rocky basin: This is a semi-closed basin that is mostly located in the mountainous areas, and it is mainly situated between three major valley systems, which are fault valleys. These valleys are: Wadi Fatima in the south, Wadi Ghoueimer in the north and Wadi Al-Bayada to the east. There are several mountain chains surrounding this basin such as Jabal Abou Jinad (about 300 m) on the northern side and Jabal Al-Shouaaba (550 m) on the south-eastern side. This regional basin comprises a number of basins in the area of concern.
2. Flattened basin: This is also a large basin situated close to the northern side of the rocky basin. It is located in a flat region (altitude of less than 150 m) surrounded

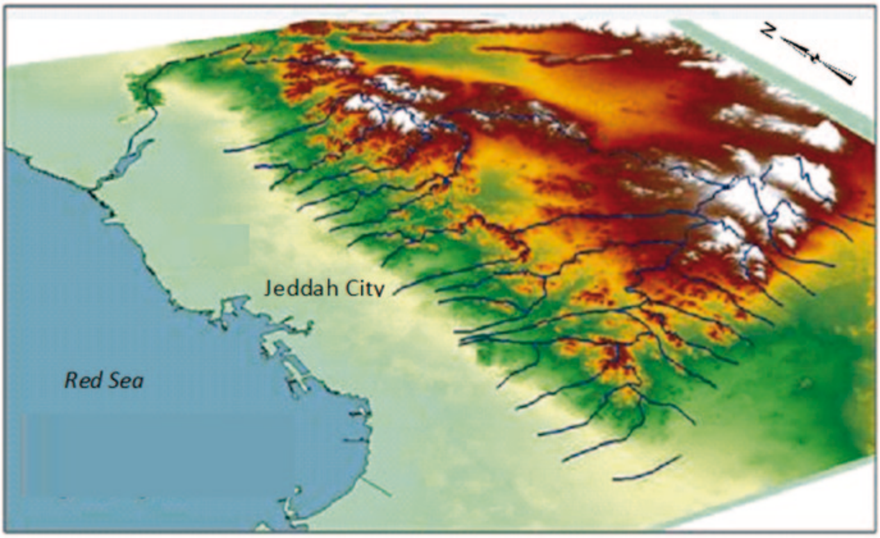

Fig. 3.4 3-D map for the study area

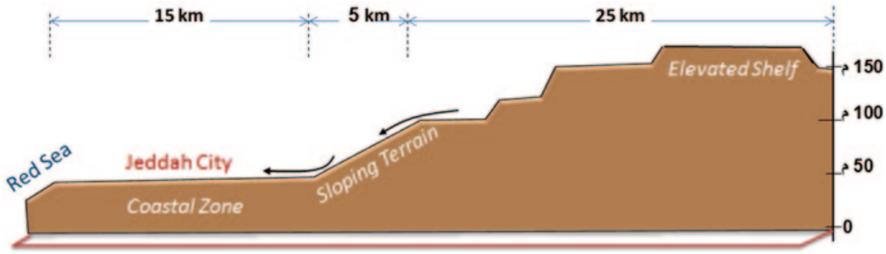

Fig. 3.5 Schematic figure showing the major shelves of the study area

by a number of basaltic mountain chains, which are represented mainly by Harat Dhahban to the north and north-east. These chains are connected with Jabal Al-Asmar to the east and south-east where an altitude of about 185 m is reached. This basin comprises the basins of Wadi Om Hableaen and Wadi Ghoueimer.

3.3.1.2 Shelves

The cross-section of the sloping terrain in the area of study largely encompasses two major terrain shelves. One is flat and the other is almost elevated, and they are joined by a moderately elevated slope (Fig. 3.5). These three terrain components play an integral role in the flow of upstream water towards the coastal zone. The cross-section of these components can be described as follows':

1. The coastal zone: This coastal shelf is situated in the west where the coastal plain can be seen as a wide ribbon that ranges between 10 and 20 km, with a slope gradient that does not exceed 3 m/km. This plain extends to about 50 km in some places, and averages an altitude of 15 m where the sites are below sea level.
2. The sloping terrain: This comprises a joining shelf between the coastal zone and the elevated regions to the east. This shelf is characterized by several valley outlets that open into the coastal zone. The width of the shelf does not exceed 5 km; it has an average altitude of about 40 m, and steep slopes in some places.
3. The elevated shelf: This is represented mainly by the mountain chains to the east of Jeddah City. It has an altitude of about 150–200 m above sea level, where some peaks exceed 500 m. The average width of this shelf is about 25 km, with an extension parallel to the coastline, and it has a slope gradient that ranges between 6 and 7 m/km.

3.3.1.3 Valleys

This section is mainly concerned with the geomorphologic characteristics of valleys. The area of study contains several valleys, most of which are wide. These valleys are often resulted due to faults, and are thus known as fault-valleys, and they exist along large-scale displacement (i.e. several kilometers). They are also characterized by thick deposits of sediment and sand that reach several meters in many places. These sediment and sand accumulations are normally resulted from aeolian erosion processes and large quantities of them are found, for example in Wadi Kawas and Wadi El-Hofna. This phenomenon exists in many other regions, such as Assfan, Tewel and Mastoura.

The dimensions of the valleys differ between regions, but are commonly wide (Fig. 3.1). The flood plains of these valleys are mainly shallow, and sometimes non-existent. This is evident by the cross-sections of the valleys and by the negligible thickness with respect to their width where sheet erosion along the flood plains is a common occurrence. The width of the valleys generally ranges between 500 and 700 m, while it may exceed one kilometer in the fault-valleys. Except in some narrow valleys, the depth does not usually exceed several meters, but losses are widespread (Fig. 3.6).

Alluvial fans are another common geomorphologic feature that exists at the foot slopes of the mountains in the study area. In addition, the hills and mountain ridges that are located along the course of river valleys affect the water flow, sometimes causing high run-off and the injection of water masses and debris. This is usually accompanied by a rise in the water level during torrential rainfall periods. It was noted that the bed load of valleys is one of the most influential factors controlling flood processes, and that these valleys are characterized by a huge bulk of sediment of different particle size.

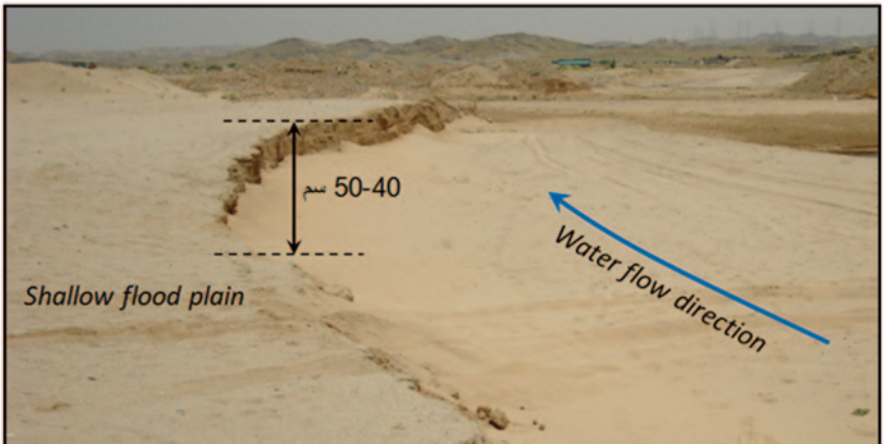

Fig. 3.6 Shallow flood plain with sediments in Wadi El-Mohrek

3.3.2 Geology

Geological setting and rock characteristics are usually investigated in studies on floods and torrents, and in some regions, the geology of terrain is considered to be the main factor controlling the flood process. In these cases, the principal hydrologic mechanisms to focus upon are the infiltration rate and water percolation into rocks and fractured surfaces. An enhanced infiltration rate results in a large amount of water being caught in the substratum, thus reducing the water bulk that may remain on the terrain surface, as well as in a slowing down of the run-off rate. In addition, unstable and non-consolidated rocks and sediments are easily eroded during flood events, and this causes an increase in the bed load that was transported by the flood water.

3.3.2.1 Lithology

The lithological sequence in the study area is principally composed of igneous, sedimentary and metamorphic rock stratum. Most of the exposed rocks are attributed to the Precambrian age, as well as to some volcanic activity. Quaternary deposits are dominant in the low-lands and in the coastal zone where a miscellany of eroded sediment from the surrounding mountains is in evidence. Accordingly, the Precambrian rocks are composed mainly of Granite, Syenite and Dolerite. In addition, there are some metamorphic rocks, such as Gneiss and Schist, and a large quantity of volcanic rocks with basalt accumulations (*Harat* in Arabic) in the area of study. The exposed rocks intensify the rate of fracture systems and joints, which enhance the infiltration rate of water. However, these rocks are mostly found in the elevated mountainous areas, and most of them are covered by sediment in the lowland areas and valleys.

Quaternary deposits also exist in the study area, sometimes with a thickness exceeding tens of meters, especially in the coastal plain where most of these deposits are saturated by saltwater.

3.3.2.2 Geologic Structures

Faults are the most important geologic structures in the area of study, where most of them are reverse faults that act with a pull-apart mechanism on different geological formations, and this results in the valley systems (i.e. fault-valleys), which are commonly identified in the area. Faults are evident from the geographic distribution of many lithologies where several vertical movements are accompanied by lateral displacement. This, in turn, controls the uplift of some the existing mountains and rocky shelves. In many instances, the tectonic activities of these faults push the rock masses for long distances, after which they take different orientations due to the high impact of the regional tectonic activity of the Dead Sea Rift System in the area. The existence of sediments and shifting sand dunes in the study area hides the alignments of many of these faults, which makes them difficult to identify using conventional methods.

The processed Aster satellite images show that many of the existing faults in the area play an integral role in the shaping of water-divide boundaries, as well as in the formation of wide valley systems, where several valleys take on the same alignment as these faults, indicating that the valleys and faults share the same orientation. However, there is no obvious linear connection (e.g. faults alignment) between the coastal zone and the mountainous areas. This confirms the hypothesis that the elevated region to the east is a result of escarpment structure rather than a faulting system. This theory is also supported by the existence of gradational slopes and no abrupt displacement.

The area of study is also characterized by many dykes and folds, as well as by joints, notably among the igneous and metamorphic rocks. However, most of them exist locally and on a small scale, while faults, which can be several kilometers long, are considered to be the largest scale geologic structures.

3.4 Urban Expansion

The increase in urban expansion has become one of the most serious environmental issues, and is often linked with exacerbating the damage caused by natural hazards. As a consequence, many countries are now giving attention to urban planning and the direction of settlement expansion. The Saudi Kingdom exemplifies the issue of urban growth, because it is considered one of the top-ranking countries worldwide in terms of population growth rate. Moreover, Jeddah City has witnessed the highest rate of population growth within Saudi Arabia[3].

Urban expansion in Jeddah City extends from the coastal zone towards the mountainous regions to the east. This can be attributed mainly to the increasing cost of land near the coast compared to more affordable prices in the mountainous regions, as well as to the crowding in coastal areas. Such expansion has also been pronounced in the northern areas towards Obher. A comparison of the analyzed satellite images retrieved in 1996 with those of 2001, as well as with topographic maps produced in 1975, makes it clear that urban expansion in Jeddah and its surroundings increased three-times over 21 years (1975–1996). While the increase ratio is 2.7 over 15 years (1996–2011). The overall estimated increase ratio in urban development is about eight-times during the last 35 years ago (Fig. 3.7).

The cause of this dramatic urban expansion is that Jeddah City is considered to be a transit station (in terms of land, sea and air travel) for people who come from all over the world to make pilgrimages and perform other religious tasks, and then remain in the city afterwards. Generally, the average rate of population growth ranges between 1.5 and 2 % worldwide, while in Jeddah City and its surroundings the population growth ranges between 20 and 28 %, and the city now contains about 3.4 million people (3500 person/km^2).

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[3] http://www.balla7mr.com/vb/showthread.php?t=28797.

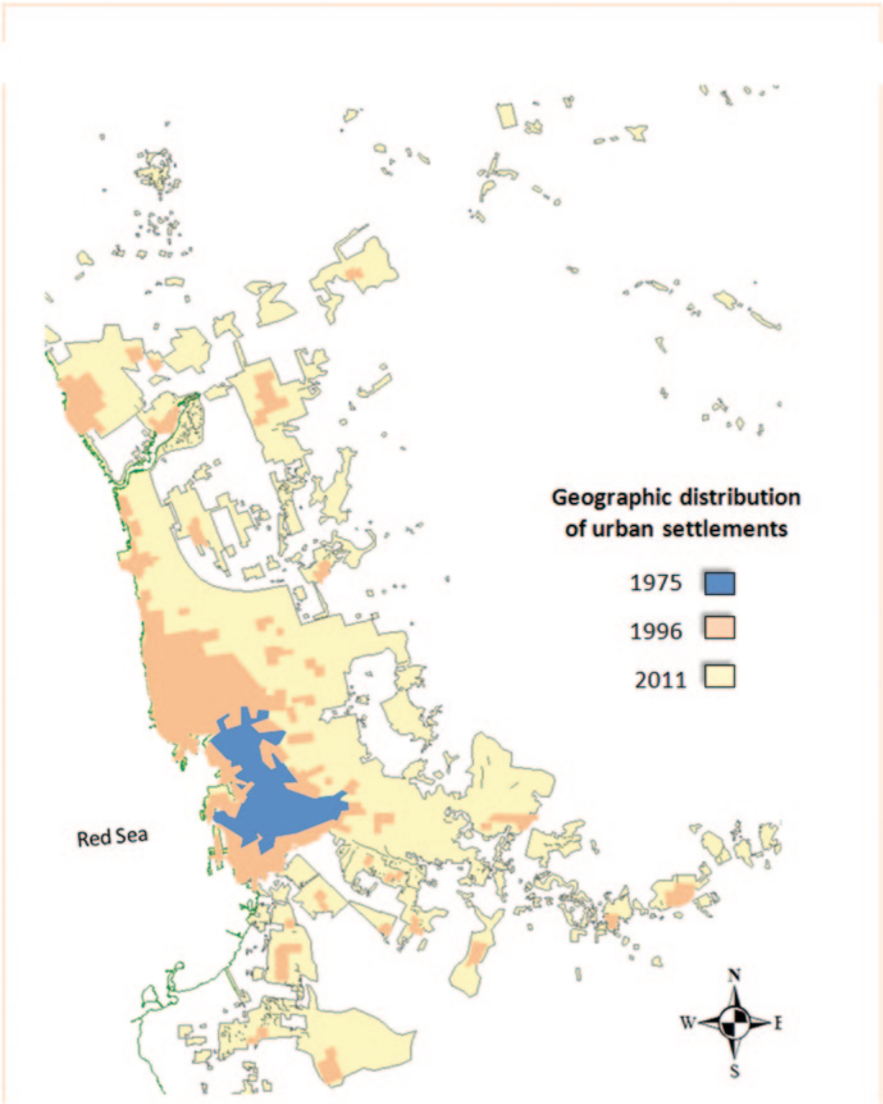

Fig. 3.7 Urban expansion in Jeddah city and the surrounding over several time periods

While urban expansion is usually viewed as a civilized development, it can sometimes have a negative impact. The latter might be the case in Jeddah City and its surroundings, where urban expansion to the east has been one of the major factors contributing to flood occurrence and the resulting damages. In the process of urban settlement, most, if not all, valley pathways were blocked, which retarded the flow of surface water towards the sea. This can result in floods and torrents, as was the case in 2009 and 2011.

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Chapter 4
Floods and Torrents in Jeddah

Abstract The city of Jeddah, along the western coast of the Arabian Peninsula, witnessed catastrophic floods and torrents in November 2009 and in January 2011. Many areas were completely submerged and the event resulted in unexpected damage to both human life and the environment. The geographic distribution and nature of the damage was identified with the aid of space technology, utilizing high-resolution satellite images acquired both before and after the floods and torrents took place.

As previously mentioned in this study, Jeddah City and the surrounding villages have witnessed a number of catastrophic episodes that resulted from floods and torrents. They occurred in November 2009 and January 2011. According to Civil Defense data resources, the two above mentioned rainfall events were the most intensive of their type since about 30 years. However, before the occurrence of these disastrous events, the matter had not been given much consideration.

Normally, zones at risk of natural hazards are identified by the integration of different geo-spatial data and information related to flood mechanisms, and the risk zones are then plotted on maps in different risk categories. However, there are often discrepancies between the information plotted on the maps and what is actually seen to occur on the terrain surface. For example, zones at risk of earthquakes are always induced according to recurrence of such events in those areas. According to this criterion, zones in Jeddah must be considered flood-prone, due to the chaotic run-off or accumulation of water in these areas. In addition, determining the risk zones helps in identifying the factors that influence the process of flooding and consequently appropriate solutions can be proposed. This practice also needs to integrate physical and anthropogenic characteristics in order to which human settlements are most at risk.

The above approach was followed in this study, and a comprehensive map showing areas prone to floods during the years 2009 and 2011 was produced. The geographic distribution of rainfall plays a major role, since there is an overlap between rainfall clusters during the two periods (Fig. 3.3). Since rainfall is a constant factor with regard to the whole area of study, other factors come into play when maps of flood-prone areas are obtained.

M. M. Al Saud, *Flood Control Management for the City and Surroundings of Jeddah, Saudi Arabia,* Springer Natural Hazards, DOI 10.1007/978-94-017-9661-3_4

4.1 Floods and Torrents in November 2009

The floods and torrents that took place in Jeddah City and its surroundings in November 2009 were distributed within a defined geographic area and this flood was more damaging than that which occurred in 2011. This is mainly attributed to the fact that the earlier flood alerted the inhabitants to the danger of such events. The geographic distribution of the flooded areas had mostly conically shaped aspects, due to the physical nature of the mountainous regions east of Jeddah City, meaning that water runs through these valleys towards the sea. This has been well observed in the areas of Al-Massaad, Kowayza, Al-Raghama and Al-Rashid (Fig. 4.1).

Through the analysis of satellite images and field verification, it has been found that flood water on the terrain surface was one of two things. It was either running water, which is almost turbid and contains debris, or water that had accumulated in roads and urban areas. In this phase of study there was a focus on the domains of the areas damaged in 2009, because of the interconnection between the disaster and damage levels, while areas which were not flooded, such as that north of Obhor, were not considered. In this instance satellite images, especially those with high spatial resolution (i.e. Ikonos images) were processed.

Envi-4.3 and *ERDAS Imagine 9.3* were used in order to facilitate electronic and digital applications for better observation of satellite images. In addition, aspects of floods and torrents were identified visually. The availability of Ikonos satellite images of the study area before and after the flood events of 2009 enabled monitoring and comparative analysis of the terrain features before and after the disaster. By these means, the areas of damage were calculated and the flow mechanism was identified.

The availability of Ikonos images also facilitated the calculation of the volume of water distributed in lakes and depressions, as well as the extent of damage in the urban areas. Thus, the geographic distribution of damaged areas was precisely determined and it was found to cover an area of about 124.58 km^2 from the total study area (688 km^2) in this phase, which is equivalent to about 18 %. This has been previously observed by the author (Al-Saud 2010a, b, and c).

The author's studies in the second phase of the same area showed that the damage in 2009 covered an area of 91.21 km^2. This discrepancy in the calculated areas is mainly attributed to the fact that in the second phase (2011) each flooded zone (any ground patch), regardless of its area, was measured. This is in contrast with the phase of 2009 where only the outer border of the damaged zones (i.e. cluster) was considered.

After the catastrophic flood and torrent events of 2009, many protective measures were immediately taken, such as the removal of debris and obstacles, the dumping of sediments in valley courses, and the construction of defenses in valley courses and around urban areas. Following this, decision makers implemented a number of more far-reaching controls to protect against such disasters, not only in the area of concern, but also in the surrounding areas.

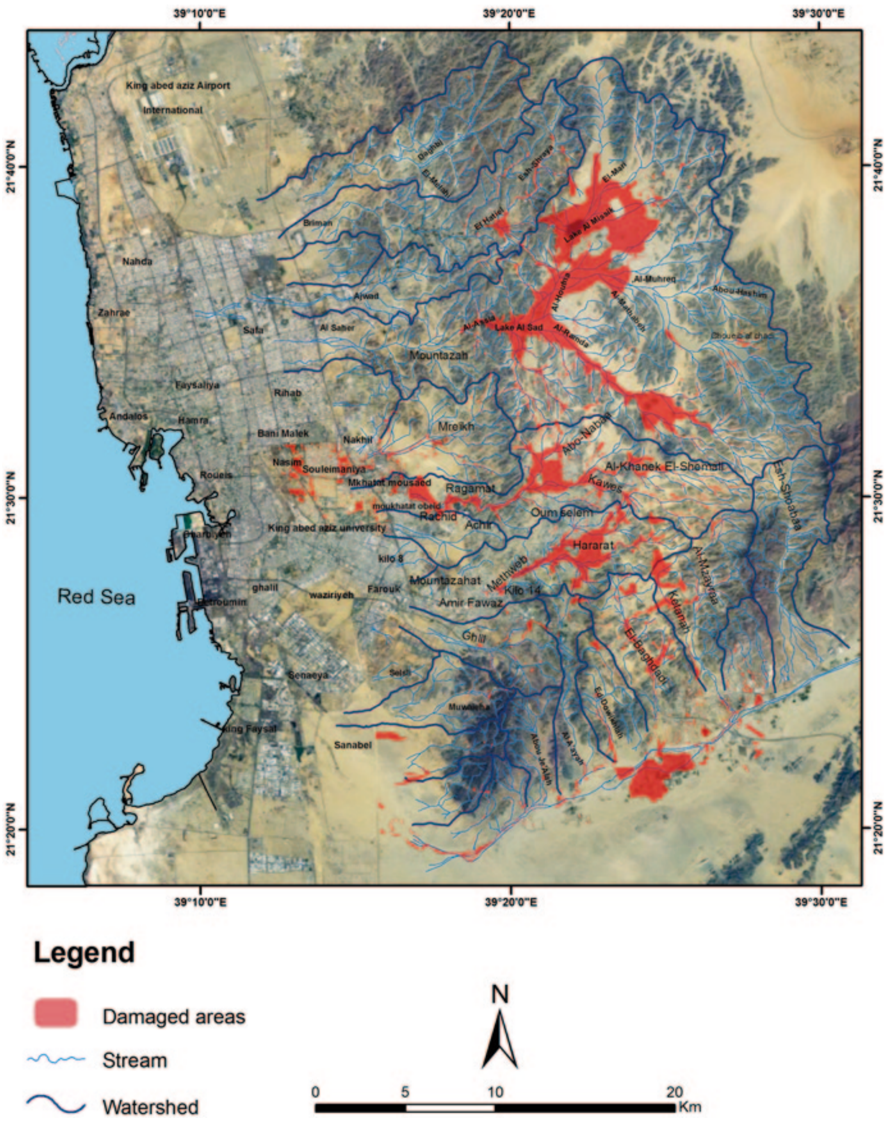

Fig. 4.1 Damaged areas by floods and torrent in Jeddah (November, 2009)

4.2 Floods and Torrents in January 2011

In January 2011, the city of Jeddah and its surroundings were subjected to another torrential rainfall peak. According to the General Corporation for Forecasting and Environmental Protection (GCFEP), rain fell at a rate between about 100 and 120 mm in a couple of hours, which is higher than that of November 2009, but the rainfall had a different geographic distribution. This was due mainly to the distribution and density of cloud masses, which were larger than those in 2009. One of these masses was located to the north-east of Jeddah City, adjacent to Obhor, while another one almost covered the entire city of Jeddah and extended to the sea (Fig. 3.3). There was no flood in this region in 2009, but it was totally covered by water in 2011. Also, some other sites which were flooded in 2009 were not affected, or only partially affected, by floods and torrents in 2011 (Fig. 4.2).

In this second phase (after January 2011), an area of about 1947 km^2 (three times larger than the study area of 2009), was studied, and the new area included two major water basins and one joining basin to the north. These basins are Wadi Ghouiemer and Wadi Om Hableen, and joining basin No. 3. On the southern side one major basin, Wadi Da'af, was included, as well as joining basin No. 28. In this case the entire coastal zone, from Obher to the north to Ar-Ras Al-Aswad- Al-Khamra in the south, was studied (Fig. 4.3). A miscellany of satellite images (see Table 2.1 and Fig. 2.2) was processed due to the unavailability of satellite images of the study area of the same type acquired directly after the disaster and also to the incomplete coverage of the available satellite scenes.

The flood damage that occurred in different zones of the study area motivated decision makers to take immediate and long-term action to protect against floods and torrents. The acquisition of sequential satellite images in Near Real-Time became a priority for the forecast and assessment of floods. The satellite images, obtained by Ikonos, World View-1, and World View-2, were used in order to have complete coverage of the area directly after the flood event.

In addition, colored Quick-Bird satellite images with high spatial resolution (0.5 m) were processed in order to monitor sites located both outside and within the area with similar topographic characteristics. In addition, Geo-eye-1 satellite images were utilized for the establishment of DEMs (Table 2.1). Using *Envi-4.3* and *ERDSA Imagine-9.3*, as well as the application of different digital processes, enabled the identification of the flood damaged zones, and also zones that were covered by water for more than a couple of days after the rainfall peak, which were therefore considered at risk of floods and torrents.

Identification of these zones enabled the determination of the domains of the areas that are subject to flood hazards. This totaled an area of about 1947 km^2 including the area studied in the first phase, which was 688 km^2, which is equivalent to only about 35 % of the new area of study. The area of the water basins (i.e. watersheds) in the area of study (of 2011) is 1403 km^2, which is equivalent to 72 % of the total study area. The rest of the zone (544 km^2) is coastal and densely populated, which means the features of the valleys are hidden. Therefore, we considered the storm-water drainages (old channel) and their extension as the limit of the water basins from the coastal zone.

Using the previously mentioned satellite images, the area of the zones damaged in January 2011 was calculated and found to be about 91.22 km^2 out of the total area (1947 km^2). This means that about 4.68 % of the area was covered either partially or totally by flood water, and this occurred during the period of the two rainfall domains as shown in Fig. 3.3.

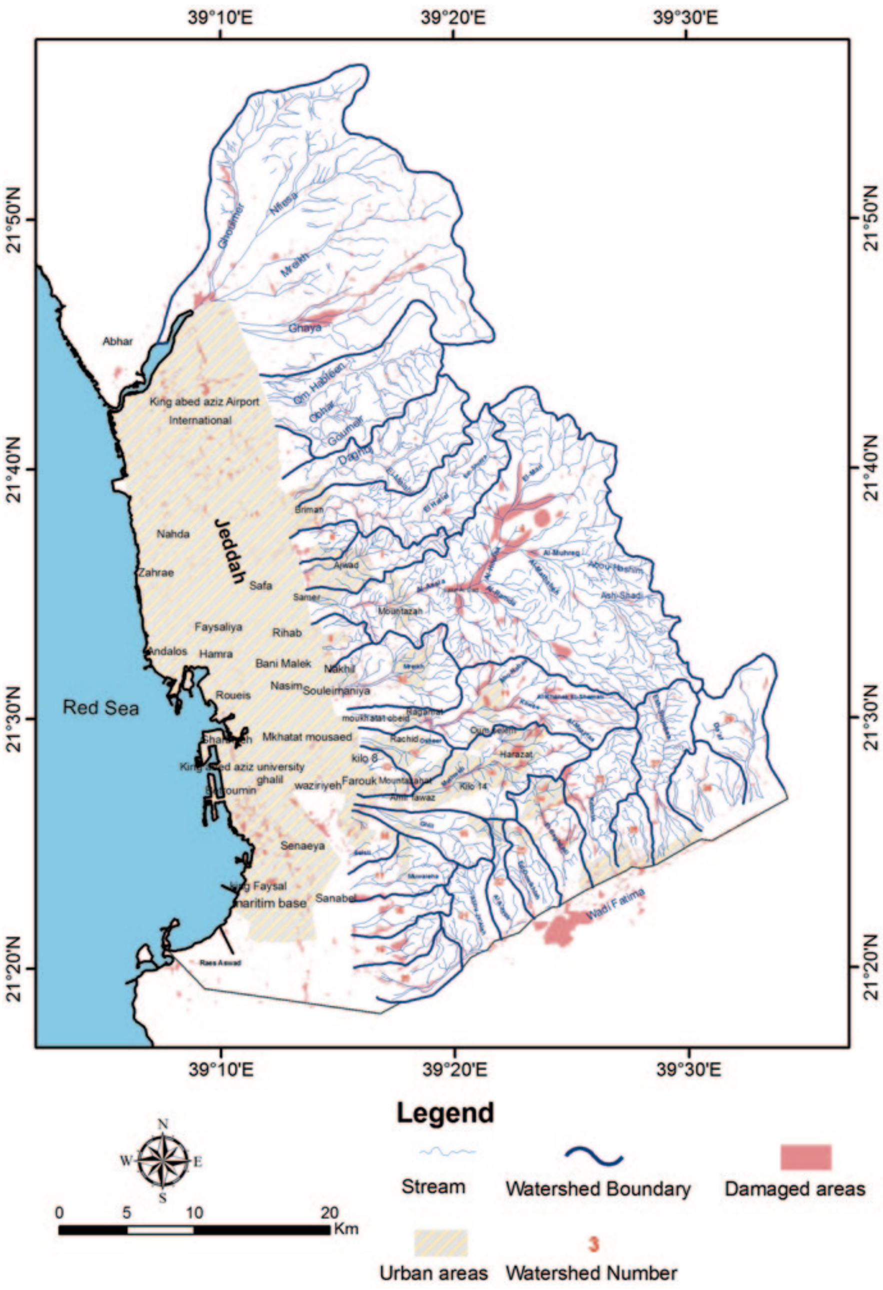

Fig. 4.2 Damaged areas by floods and torrents in Jeddah in January, 2011

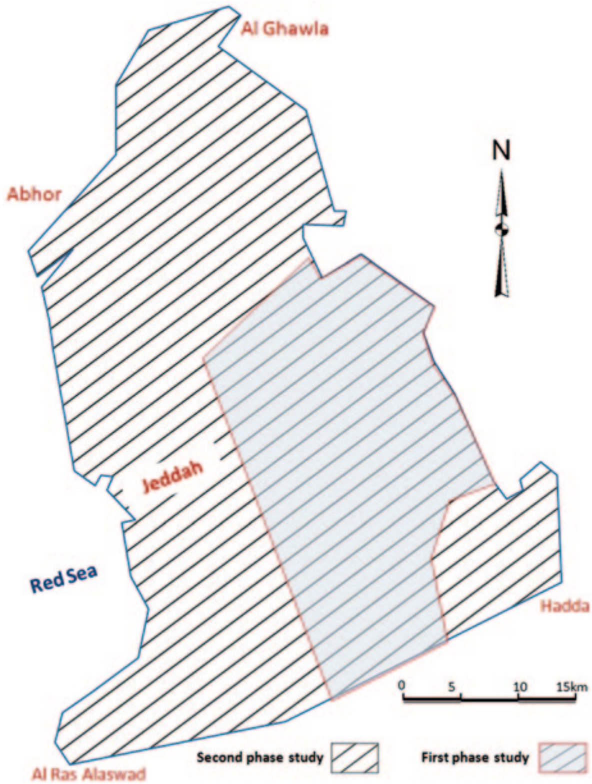

Fig. 4.3 Study area for the 1st phase (2009) and 2nd phase (2011)

4.3 Distribution of Floods and Torrents in Jeddah

After the two phases of study, and having identified zones at risk of floods and torrents in the two events, all available digital data and information were integrated and plotted on a unique map showing the flood damage in Jeddah City and its surroundings (Fig. 4.4). This was accomplished by identifying 10491 sites (polygons and digitizing the information and data). In the total area of 1947 km^2 these sites were subject to floods and torrents. Since data on the damaged zones were electronically digitized in the Geographic Information System, it was possible to calculate the area of each identified site and then apply the appropriate classifications. In addition, damaged zones in each basin were identified and thus the relationship between the geographic distribution and the hydrologic and geomorphologic characteristics of floods and torrents could be inferred. Table 4.1 shows the area of the damaged zones in each basin.

Figure 4.4 shows the impact of floods and torrents, as well as the geographic distribution and dimensions of the resulting damage. The area damaged over the two periods was estimated at 146.5 km^2 which is equivalent to 7 % of the study area. This percentage is of course governed by the intensity of the rainfall, which ranged

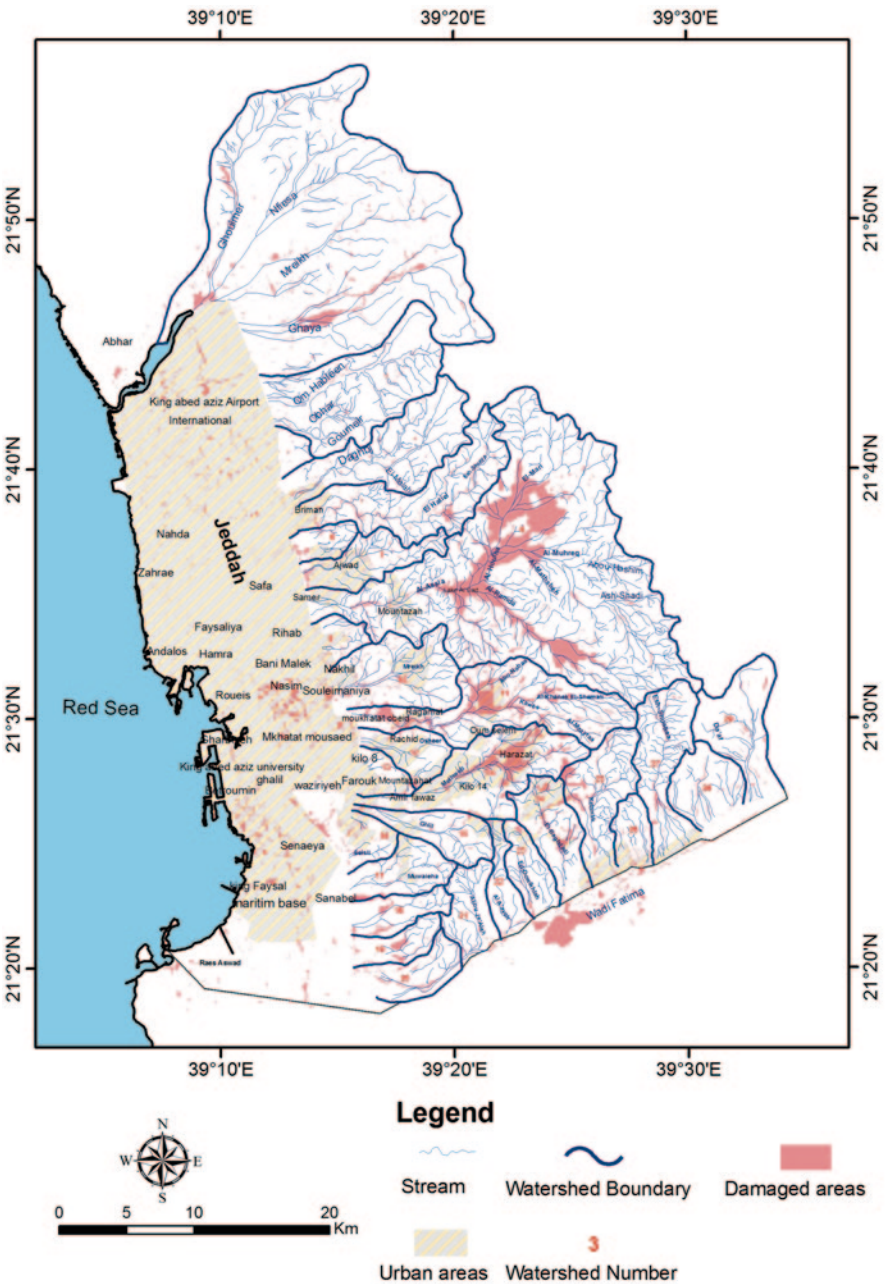

Fig. 4.4 Damaged areas by floods and torrents in Jeddah during 2009 and 2011

between 95 and 120 mm over the two periods. This means that an increase in the rainfall rate will result in more damage. This highlights the importance of implementing proper controls to mitigate the impact of such a disaster.

Table 4.1 Damaged area in each water basin

No.	Watershed	Damaged area (km^2)	No.	Watershed	Damaged area (km^2)
1	Ghouiemer	13.10	16	Selsli	0.99
2	Om Hableen	1.99	17	Muwaieha	1.15
3	Basin # 3	0.08	18	Basin # 18	1.42
4	Daghbj	1.64	19	Basin # 19	1.45
5	El Hatiel	4.29	20	Basin # 20	1.61
6	Basin # 6	0.77	21	Abou Je'Alah	0.48
7	Basin # 7	1.53	22	Al A'ayah	0.42
8	El Assla	48.16	23	Ed-Dowikhlah	0.82
9	Basin # 9	0.76	24	El-Baghdadi	3.42
10	Mreikh	3.40	25	Ketanah	3.40
11	Kawes	14.48	26	Basin # 26	0.57
12	Osheer	0.74	27	Esh-Shoabaa	1.62
13	Basin # 13	0.38	28	Basin # 28	0.77
14	Methweb	10.26	29	Da'af	1.19
15	Ghlil	0.78			

4.4 Aspect of Floods and Torrents Distribution in Jeddah

It was clear that there is a difference between areas with respect to the geographic distribution of water bodies that resulted from floods and torrents. The largest masses were found to accumulate mainly in the mountainous regions and on sloping terrain. The six major aspects of geographic flood distribution (Fig. 4.5) are as follows:

1. *Transported water and sediments*

This usually occurs in relatively elevated zones (i.e. mountainous areas) that slope towards the zones with less elevation (mostly coastal plains). They usually extend for long distances of several kilometers according to the orientation of the sloping terrain, as when valleys in the east extend towards the sea (Fig. 4.5a).

Usually, flood water of this aspect carries a mixture of sediment and mud, as well as rock debris, which increases the energy flow of the running water, which then has the power to dislodge obstacles in its way, as happened in Wadi Kawas.

2. *Injected flow*

This phenomenon was found to be dominant in the area of study, notably where mountains and hills are located in the valleys and form obstacles to the water flow (Fig. 4.5b). Running water in wide valleys impacts with these mountains and hills where the width of the valley decreases. This results in sediments being injected into the water, which in turn increases in power in the narrow sections between these obstacles. This is the most dangerous aspect of the water distribution that results from floods and torrents. Kowayza and Al-Massaad are clear examples of this occurrence.

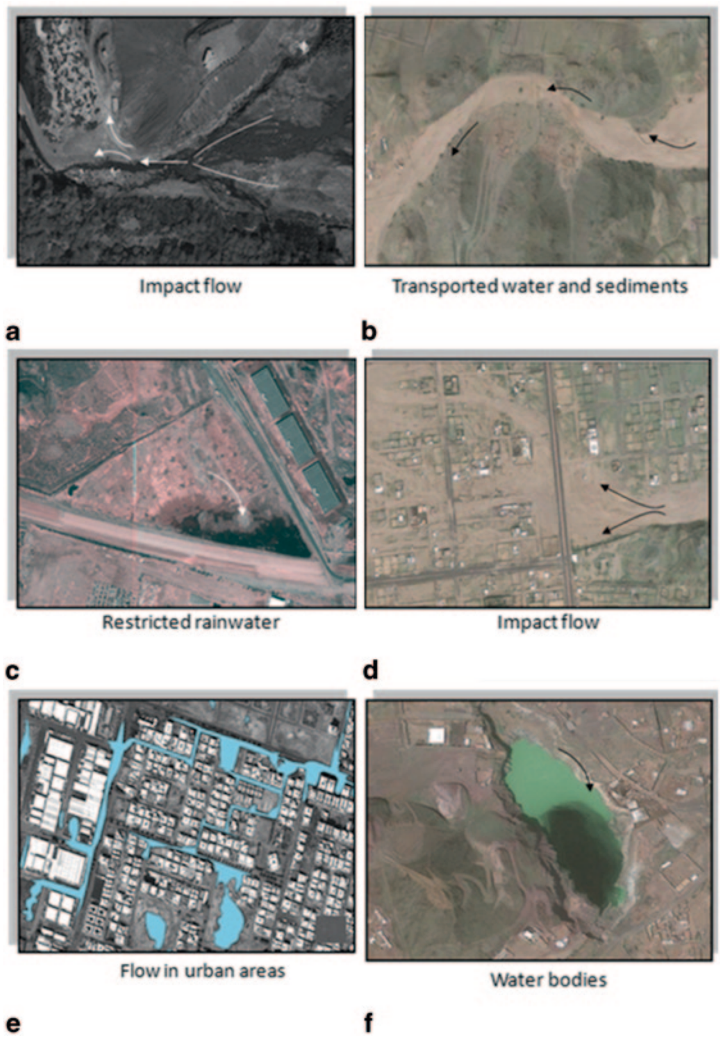

Fig. 4.5 Aspects of geographic distribution of floods and torrents in Jeddah area

3. *Impact flow*

This refers to the flood water which results from the impact between running water and urban settlements. This aspect of flood distribution usually carries a heavy bed load (Fig. 4.5), which is mainly attributed to the construction of urban sites in the valleys. It is common in many localities in the area of study due to the lack of proper urban planning.

4. *Restricted rainwater*

This refers to the rain water which is restricted in confined urban localities and between constructions. The bodies of water that accumulate in urban settlements are

Fig. 4.6 Water accumulation due to groundwater level rise in Al-Adel region

Fig. 4.7 Water accumulation along Briman road

usually shaped according to the layout of the buildings, and they may accumulate in areas surrounded by sediment barriers or on roadsides (Fig. 4.5d). This aspect is common in areas where the water level rises (Fig. 4.6). It has little or no negative impact.

5. *Water bodies*

This refers to accumulations of water in natural depressions or between adjacent mountainous masses (Fig. 4.5e). This type of flood water is usually clear (not turbid). The sites where water accumulates should be viewed from an investment point of view, in that such water is available for harvesting.

6. *Flow in urban areas*

This is also accumulated rainfall, but these bodies of water run between roads and often take on an aspect totally consistent with the road alignments (Fig. 4.5). This type of water may be turbid but usually has little sediments. It is widespread in several localities in Jeddah City (Fig. 4.7).

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Chapter 5
Hydrological Analysis of DEMs

Abstract There are many tools for terrain analysis, whether for introducing the geomorphologic aspects of different surfaces or for identifying the water flow mechanism along these surfaces. Digital Elevation Models (DEMs) have recently emerged to be a useful tool in this respect. In the present study, DEMs supported data obtained from space observations and proved to be an integral element in flood analysis.

Recently, Digital Elevation Models (DEMs) have had widespread applications in several geomorphological and hydrological studies (Maune 2007), especially since this model enables the extraction of topographic features on the terrain surface, and makes it possible to display all the natural features with both vertical and horizontal resolution (i.e. in 3-D). Different methods are used to extract the terrain elevation data of topographic features in order to build DEMs, and the accuracy of the resulting DEMs is dependent on data availability and precision. Moreover, the interpretation and analysis of DEMs varies between studies.

DEMs can be built by identifying the elevation points on the terrain surface with defined geographic coordinates. Digital topographic maps, with contour lines plotted on specialized software, are usually used for this purpose. If these maps are not available in a digital format, however, high-resolution satellite images with stereoscopic visualization can be utilized to produce high-precision DEMs. In the present study, Geo-eye-1 satellite images with 2 m spatial resolution were used. These images were firstly converted into digital contours, at the King Abdulaziz City for Science and Technology (KACST).

As mentioned above, the extracted DEMs are analyzed and interpreted in different ways, governed by the type and purpose of the study in the case of hydrologic investigations, whether the interest is in assessment of flow regime or flood processes. DEMs can provide essential signatures of the natural setting and behavior of the terrain surface, and data resulted from DEMs can be used to induce water flow regime in different geographic areas.

In dealing with DEM data, the natural terrain signatures must be considered. It is well known that surface water follows the natural pathways; that is, it runs on the terrain surface according to the slope of the surface. The water continues to flow unless the slope becomes minimal in which case it accumulates. During

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this journey, the bulk of the water is concentrated in valleys, while some may accumulate in depressions. The major factors controlling water flow on the terrain surface can be calculated and the mechanism can be induced by the use of DEMs. In this study, DEMs were built and the resulting data was analyzed in order to determine terrain slope, valley cross-sections and channel slope, and also to identify the location of depressions. The first three parameters interact to govern water flow from different surfaces towards the valleys, and then to convey it to the final outlet. These parameters will be considered in determining the factors that influence floods and torrents.

5.1 Terrain Slope

The terrain slope of the Earth's surface is considered to be one of the geometric parameters that control the water flow system and also consequently flooding. Therefore, the slopes of terrain surfaces and not those of valley beds are the ones to be investigated. Normally, the higher the slope rate (angle with horizon) of surrounding surfaces, the higher the velocity of flow from these surfaces to a specific valley. The valley will capture the water and water level will rise, maybe overflowing onto the flood plains. In order to calculate these geometric variables from DEMs, each hydrologic system must be treated separately (a number of surfaces in defined direction, which is mostly attributed to sub-catchments). Since these variables will be used to study the overland flow, it is necessary to analyze the values of each basin in the study area. These basins are composed of a number of surfaces extending towards valleys. If the area within the basin is classified by identifying different surfaces with slopes, an empirical assessment can be made with regard to the effectiveness of the total number of slopes in each basin in the area of study. This can be done by establishing DEMs in the GIS system, and more certainly in *Arc GIS* software, as was the case in this study (example in Fig. 5.1).

In this regard, the inclination of surfaces is usually treated as a linear component and thus described as "Length slope (L_s)" in many studies (e.g. Khorsowpana et al. 2007), and the total area of the surfaces is not considered. In order to

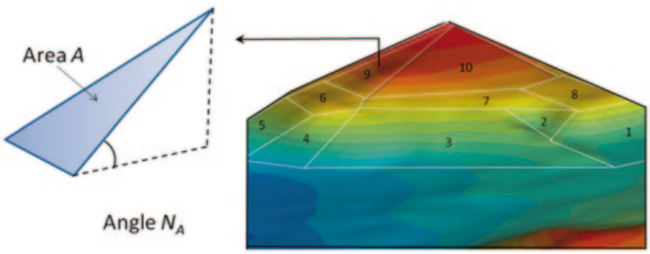

Fig. 5.1 Classifying terrain surfaces on DEMs in order to calculate water flow effectiveness

estimate the effectiveness of the surfaces in terms of the energy of the water flow, it is necessary to classify the area (basin) as possessing several surfaces, each one being characterized by a certain defined slope N_a. Hence, there is a direct proportionality between the surface slope and its area (i.e. multiplied variables), and the effectiveness (S_t) can be calculated for the existing surfaces (N_s). Consequently, the average of all values can be determined in each basin according to the following equation:

$$S_t = \frac{A_1 x N_{a1} + A_2 x N_{a2} + A_3 x N_{a3} + \ldots\ldots}{N_s}$$

In order to apply this equation, angles of the surfaces are categorized from 0 to 90°.

This geometric concept cannot be applied to flat (e.g. coastal) regions in the city of Jeddah and its surroundings, because of the low slope. In addition, urban settlement may reduce the effectiveness of this concept. Therefore, the required variables of the 29 basins in the study area were calculated from the high mountains to where dense urban settlement begins, thus excluding the coastal zone (Table 5.1).

Normally, in large-scale basins (such as the basins of Wadi Ghouiemer and Wadi El-Assla), the total area of surfaces will be higher than those in the small-scale basins (e.g. the basins of Wadi Osheer and Wadi Ghlil), but it is not necessary to witness floods in the large-scale basins, because the concept here implies the interaction between the surfaces in each valley and not the area of the valley. Therefore, this parameter cannot be applied separately, but needs to be applied in a comparative integration between the effectiveness of the slopes and the discharge capacity, which is represented mainly by the area of valley cross-section and the channel slope. This means that it is necessary to consider the ratio between the capacity and discharge (i.e. output-input from the system). In other words, the increase in the cross-section area of the valley will increase the capacity of the channel which is derived from the surrounding surfaces; also, when the channel slope increases the flow, energy will be increased, along with the discharge. It is thus necessary to conduct a comparative analysis in order to induce the ratio between the total sloping surfaces according to the cross-section area of valleys and their slopes (i.e. channel slopes).

5.2 Valley Cross-Sections

The properties of valley cross-sections are covered in many geomorphologic and hydrological studies, since these studies are concerned with evaluating the capacity of watercourses and the mechanisms of water flow and bed load, whether with regard to flow energy or erosion and sedimentation processes. However, valley cross-sections do not act separately on the hydrological system, but interact with other hydrological and geomorphologic properties. Therefore, it is necessary to investigate the interaction between different properties as was mentioned in the previous section (Terrain slope).

Table 5.1 Terrain slope effectiveness in water basins after values calculations from DEM

Basin No.	Basin	(Na)	(A) km^2	Average slope effectiveness (º)	Total effectiveness (St)
1	Ghouiemer	23	12.8	8°	Medium
2	Om Hableen	16	0.84	10°	Medium
3	Basin # 3	2	0.48	3°	Low
4	Daghbj	20	1.02	15°	High
5	El Hatiel	17	0.96	11°	High
6	Basin # 6	3	0.65	4°	Low
7	Basin # 7	5	2.74	12°	High
8	El Assla	32	5.72	7°	Medium
9	Basin # 9	3	1.43	4°	Low
10	Mreikh	9	1.88	7°	Medium
11	Kawes	18	2.12	9°	Medium
12	Osheer	5	0.98	5°	Low
13	Basin # 13	2	1.97	4°	Low
14	Methweb	13	2.05	11°	High
15	Ghlil	7	0.78	4°	Low
16	Selsli	2	0.27	1°	Low
17	Muwaieha	5	1.58	8°	Medium
18	Basin # 18	4	1.18	6°	Medium
19	Basin # 19	3	0.78	2°	Low
20	Basin # 20	1	0.58	1°	Low
21	Abou Je'Alah	5	1.08	9°	Medium
22	Al A'ayah	4	1.49	7°	Medium
23	Ed-Dowikhlah	8	0.97	5°	Low
24	El-Baghdadi	17	1.07	12°	High
25	Ketanah	19	1.24	14°	High
26	Basin # 26	7	0.58	15°	High
27	Esh-Shoabaa	19	1.22	17°	High
28	Basin # 28	9	1.13	13°	High
29	Da'af	14	1.76	15°	High

Channel slope must also be considered in studies on floods, since it plays a role in accelerating or reducing the water flow rate. This property will be evaluated in detail in the next section, and in conjunction with terrain slope and valley cross-sections, used to induce a complete mechanism of the water movement in each basin.

The major variables of the valley cross-sections are: width, depth and length of the primary watercourses. In addition, the depth and width of flood plains must be taken into account, notably where they are shallow, as many in the study area are. In this case, water may overflow into the flood plains when the water level rises

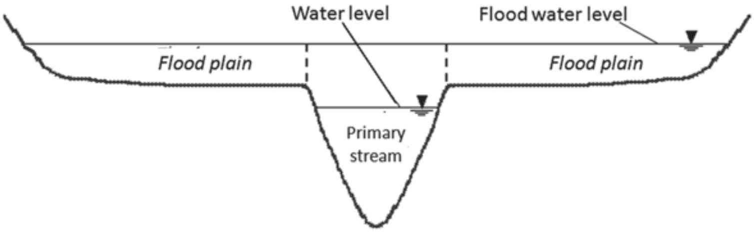

Fig. 5.2 Typical valley cross-section with major geomorphologic elements

and even when it is at a low level, because the difference between depths (primary watercourse and flood plain) is relatively low (Fig. 5.2).

Normally, the width and depth of water channels is not constant and varies along segments of their length. Therefore, in order to evaluate the capacity of each channel, it must be divided into segments, and the depth, width and length of each segment should be calculated. The length of the segments is determined according to changing width or to stream meandering.

Having measured the three geometric variables (i.e. length, width and depth) of each segment included along the primary channel course, as well as those of the flood plains of these channels, the total section area (Xt) can be calculated as follows:

$$X_t = \frac{\left[(W_{m1} x D_{m1}) + (W_{f1} x D_{f1})\right] x L_1 + \left[(W_{m2} x D_{m2}) + (W_{f2} x D_{f2})\right] x L_2 \ldots\ldots}{N_{sg}}$$

Where:

W_{m1} is the width of the main stream, No. 1
D_{m1} is the depth of the main stream, No. 1
W_{f1} is the width of flood plain No. 1
D_{f1} is the depth of flood plain No. 1
L_1 is the section length
N_{sg} is the number of channel segments

The geometric variables can be calculated using DEMs, if the latter are characterized by high precision that fits with the existing width and depth of cross-sections. The classification of these segments was done following a systematic procedure in *Arc-GIS* software (Fig. 5.3). Hence, the required variables for every segment can be sorted into tables (Table 5.2).

The above procedure must be followed with regard to the adjacent surfaces of the identified segments, and applied to each basin separately (Table 5.2). In other words, calculations are applied (as shown in Sect. 5.1 and 5.2) depending on defined terrain surfaces adjacent to the valley course, and they must be applied to all basins in the study area.

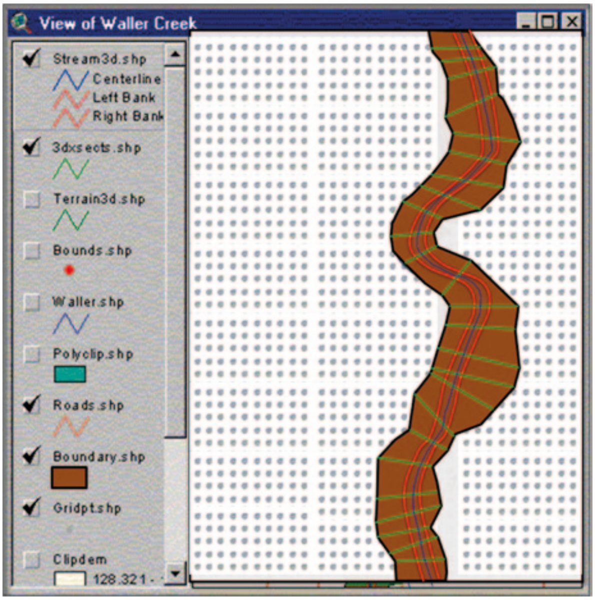

Fig. 5.3 Example on calculating the channel width variables by *Arc-GIS*

5.3 Channel Slope

In addition to the slope of terrain surfaces located on the adjacent sides of valleys, the slope gradient (degree of inclination) of the stream channel is also an essential parameter in flood assessment. It is well known that the rate of water flow increases with the increase of the slope gradient of the stream channel. The flow rate in turn acts in accelerating the discharge rate of the channel itself, and this may be catalyzed by erosion processes. Also, the slower the flow rate, the slower the discharge process, and the consequent sedimentation that occurs reduces the probability of flood occurrence. Hence, channel slope plays a double role in the flooding mechanism.

The channel slope is calculated using the following simplified equation:

$$\frac{L}{\ddot{A}h} = \frac{\text{length of the channel}}{\text{Difference in elevation}}$$

However, stream channels are characterized by different slope gradients. Morisawa's (1976) equation (below) can be used to estimate the channel slope at different points along this channel.

Channel slope = (E 0.85 L)−(E 0.10 L)/E 0.75 L

(Where E is the elevation and L is a point along the channel)

For example, (E 0.85 L) means an elevation at 85 % distance at the upstream of the channel, and so on for the rest of the values in the above equation. However, in the case of DEM data availability, calculating the channel slope can be done more accurately and reliably than by mathematical equations. DEMs can be used after the channel has been divided into segments (as in Sect. 5.2) to calculate the slope

Table 5.2 Water-bearing capacity in valleys according to their cross-sections

Basin No.	Basin	No. of channels	Average surface for cross section (Xt) km^2	Total effectiveness (St)
1	Ghouiemer	4	0.126	Medium
2	Om Hableen	2	0.215	High
3	Basin # 3	1	0.095	Low
4	Daghbj	2	0.128	Medium
5	El Hatiel	2	0.075	Low
6	Basin # 6	1	0.102	Medium
7	Basin # 7	1	0.087	Low
8	El Assla	8	0.121	Medium
9	Basin # 9	1	0.230	High
10	Mreikh	1	0.183	High
11	Kawes	4	0.182	High
12	Osheer	1	0.105	Medium
13	Basin # 13	1	0.021	Low
14	Methweb	1	0.099	Low
15	Ghlil	1	0.258	High
16	Selsli	1	0.177	High
17	Muwaieha	1	0.183	Low
18	Basin # 18	1	0.172	High
19	Basin # 19	1	0.114	Medium
20	Basin # 20	1	0.247	High
21	Abou Je'Alah	1	0.084	Low
22	Al A'ayah	1	0.097	Low
23	Ed-Dowikhlah	1	0.073	Low
24	El-Baghdadi	1	0.035	Low
25	Ketanah	1	0.045	Low
26	Basin # 26	1	0.046	Low
27	Esh-Shoabaa	1	0.076	Low
28	Basin # 28	1	0.104	Medium
29	Da'af	1	0.062	Low

gradient of several defined segments. The DEMs analysis method was followed in this study and the results are shown in Table 5.3, where they represent channel slopes of each of the major valleys.

Having measured the three fundamental parameters (terrain slope, cross-section and slope of the channels)which are required to assess the channel capacity and water flow mechanism, it is necessary to integrate these parameters. Of course, there are other parameters (e.g. lithology, green cover, etc), which may have an influence on water flow regime, but not at the same level as the three mentioned here.

If water bulk flowing from surfaces into channels exceeds the channel discharge, then the water level will become higher than normal and flood will occur; whereas

Table 5.3. Water capacity in channels and its susceptibility to floods as indicated from channel slope

Basin No.	Basin	No. of channels	General slope gradient (m/km)	Total effectiveness
1	Ghouiemer	4	16	Medium
2	Om Hableen	2	18	Medium
3	Basin # 3	1	23	High
4	Daghbj	2	28	High
5	El Hatiel	2	19	Medium
6	Basin # 6	1	7	Low
7	Basin # 7	1	13	Medium
8	El Assla	8	16	Medium
9	Basin # 9	1	6	Low
10	Mreikh	1	13	Medium
11	Kawes	4	19	Medium
12	Osheer	1	11	Medium
13	Basin # 13	1	8	Low
14	Methweb	1	16	Medium
15	Ghlil	1	14	Medium
16	Selsli	1	4	Low
17	Muwaieha	1	7	Low
18	Basin # 18	1	10	Low
19	Basin # 19	1	9	Low
20	Basin # 20	1	6	Low
21	Abou Je'Alah	1	17	Medium
22	Al A'ayah	1	19	Medium
23	Ed-Dowikhlah	1	18	Medium
24	El-Baghdadi	1	27	High
25	Ketanah	1	34	High
26	Basin # 26	1	33	High
27	Esh-Shoabaa	1	36	High
28	Basin # 28	1	18	Medium
29	Da'af	1	29	High

if the discharge rate is higher, the water flowing from surfaces will not be given the chance to accumulate and no flood will occur.

In this study, the three calculated parameters, which were integrated in an empirical approach, depended on the values calculated from DEMs. Then, a graphic comparison was made of the different components of these parameters (i.e. terrain slope, cross-section and slope of the channels). This was done in order to assess the role of these parameters in the occurrence of floods and torrents (Fig. 5.4).

The higher values of these parameters have a double impact. For example, an increase in surface slope increases the effectiveness of floods, while an increase in

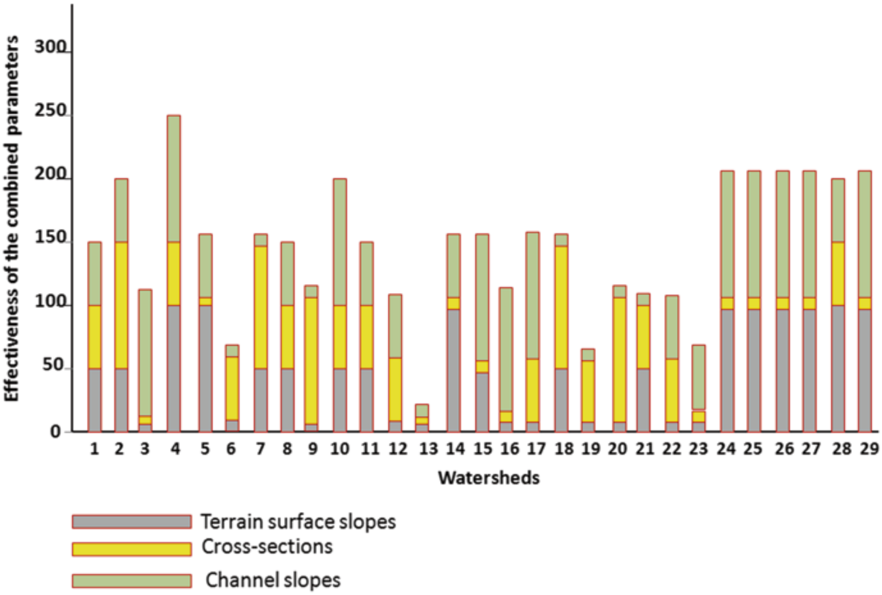

Fig. 5.4 Effectiveness of the combined parameters on floods and torrents in the watersheds of the study area

the cross-section area, as well as in the channel slope, will reduce flood probability. Hence, in the graphical illustration, the reversible-effectiveness values (for the cross-section area and the channel slope) were considered. Thereafter, the different impact of each parameter was established (as in Fig. 5.4) to show their degree of effectiveness in the occurrence of floods and torrents.

For assessment to be consistent, all of the values were ascribed percentages: higher effectiveness was attributed at 100 % for each parameter, thus totaling a maximum value of 300.

Figure 5.4 shows that some basins are more susceptible to floods and torrents (e.g. Wadi Daghbj, basin No.4) than other ones (e.g. basins No. 6 and 13). Of course, this assessment is made only on the analysis of three hydrological parameters (in Sect. 5.1, 5.2 and 5.3). The probability of flood occurrence may change in these basins if other influencing parameters are involved, and this will be discussed in the next sections.

5.4 Depressions

The geomorphology of depressions differs between regions; some of them are attributed to folding in the terrain surface, while others are due to geological deformations (e.g. fracturing systems, subsidence in the Earth's surface, dissolution in

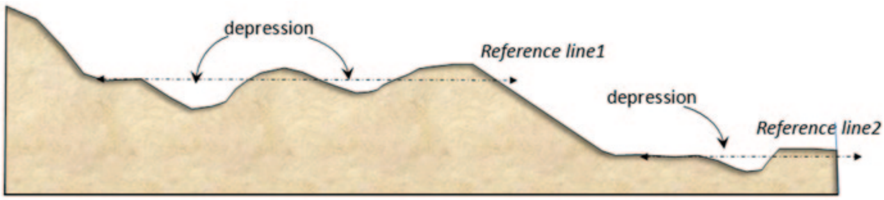

Fig. 5.5 Schematic illustration showing the concept of reference lines

carbonate rocks). Still other depressions are created by human activities, notably during construction and land reclamation.

Depressions are considered important terrain features with regard to floods. They play a double role in surface water flow and water accumulation. Naturally, a depression retards water movement and may restrict water bodies on the terrain surface. As well as this, a depression can capture direct rainfall, but any floods that may result are relatively low risk due to the negligible water flow.

Generally, it is not easy to identify depressions and low-lands directly from satellite images; especially in dry seasons, and this is also the case with topographic maps, unless they are constructed with small contour interval values. The capacity of depression has a role in determining the volume of water that can accumulate at different levels. However, DEMs provide valuable information in drawing depressions, particularly if high-resolution DEMs are interpolated, as was the case in this study, which followed a new concept for the identification of these features. This concept depends fundamentally on the build-up of "*Reference lines*" on the terrain surface, at defined elevations of a specific area or basin for example. Figure 5.5 shows an example of the selection of reference lines.

Reference lines are constructed using *Arc-GIS* software, and by connecting the levels of the flat areas with respect to the horizontal alignment (as a reference line). Consequently, any level below these lines is considered to be part of the depression or low-land area. During this systematic procedure, "masking" is also applied to all objects higher than the selected reference lines; thus, depressions exist as closed topographic clusters that can be clearly discriminated from the surrounding topography (Fig. 5.6).

Table 5.4 shows the total areas with depressions and low-lands in each basin of the study area. However, not all the identified depressions are of a natural origin; many are the result of human excavation. These latter are commonly observed in the study area where water has accumulated between different constructions and buildings (e.g. planned areas, roads, etc). As a result of this, and after analyzing the satellite images acquired directly after the floods of November 2009 and January 2011, depressions and low-lands were instantly recognized, and even their traces (i.e. various sediments, lamina) were identified due to the existed mud accumulation and cracks. In the light of all this, DEMs are now considered to be a valuable tool in the assessment of floods and torrents even for areas that have not yet witnessed them.

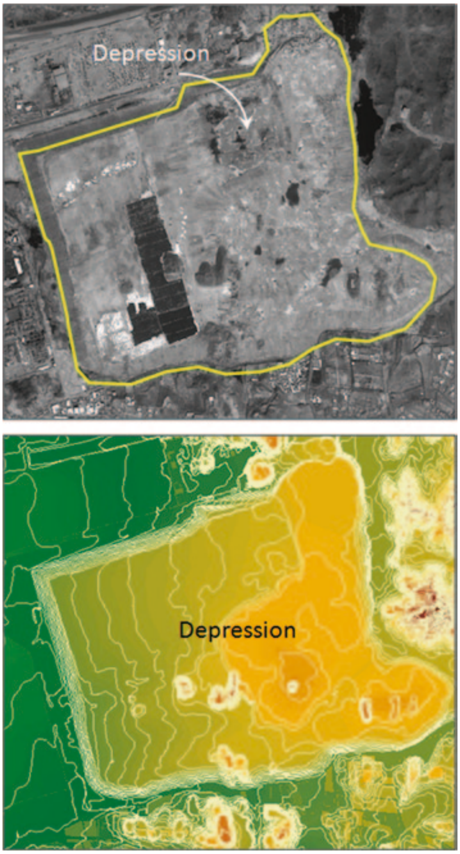

Fig. 5.6 Example showing a depression as observed from satellite image and in DEM

Table 5.4 Areas of depressions in different watersheds

Basin No.	Basin	Total depressions area (km^2)	Basin No.	Basin	Total depressions area (km^2)
1	Ghouiemer	6.52	16	Selsli	0.35
2	Om Hableen	2.13	17	Muwaieha	1.81
3	Basin # 3	0.35	18	Basin # 18	0.73
4	Daghbj	1.86	19	Basin # 19	0.53
5	El Hatiel	2.14	20	Basin # 20	1.04
6	Basin # 6	0.12	21	Abou Je'Alah	1.54
7	Basin # 7	1.05	22	Al A'ayah	0.88
8	El Assla	11.24	23	Ed-Dowikhlah	1.17
9	Basin # 9	0.83	24	El-Baghdadi	0.46
10	Mreikh	2.19	25	Ketanah	0.37
11	Kawes	2.88	26	Basin # 26	0.24
12	Osheer	1.22	27	Esh-Shoabaa	0.87
13	Basin # 13	0.24	28	Basin # 28	1.43
14	Methweb	3.05	29	Da'af	0.34
15	Ghlil	1.34			

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Chapter 6
Geometric and Morphometric Analysis of Drainage Systems

Abstract The geometric and morphometric analyses of drainage systems have become accepted tools in the study of floods and torrents. Such analyses depend on well known geomorphologic formulas and concepts, whether for diagnosing the outer boundary of a water basin or for analyzing the interrelation of streams. However, these formulas are now being supported by space technology and DEMs. This chapter describes the different aspects of geometric and morphometric analyses used in flood investigation.

6.1 Geometric Analysis of Drainage Systems

The geometric shaping of drainage systems (i.e. water basins) is considered to be one of the key factors that control the mechanism of the geographic distribution of water on the terrain surface. In this study, geometric parameters are considered for water basin boundaries without taking into account the morphometric parameters located for this basin. Thus, the shape of the water basin, as well as the elongation rate and rotation rate, are the most important factors.

There are several geometric patterns that characterize the outer shape of a water basin, and each of them plays a role in the run-off process from the upstream area along slopes to reach the downstream and outlet area. The basin's shape governs the branching process of tributaries, and thus the flow regime (Black 1991). For example, basins with a circular shape have regular water discharge from their tributaries, and consequently water from different directions can reach the outlet almost at the same time. But this is not the case in basins with an oval shape where there is a difference in the discharge process according to the run-off time, and therefore they are considered to be less susceptible to floods. There are several characteristics for specifying the shape of water basins, and the most important ones are the following:

6.1.1 Length/Width Ration

The ration between the basin length and its width (L/W) is an indicator of surface flow effectiveness, and thus an increase in the ration of width compared to the

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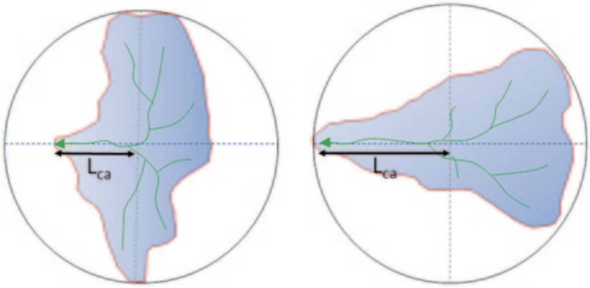

Fig. 6.1 The shape factor representation for water flow regime

length will extend the time of flow duration and vice versa; whereas the average value of this ration in ordinary basins is 0.5, which means that the basin length is equal to about twice its width. This can be defined by the following simplified equation:

$$\frac{L}{W} = \frac{\text{Basin length}}{\text{Basin width}}$$

6.1.2 Shape Factor (S_f)

The factor that controls the shaping of a water basin is determined according to its central length (L_{ca}), which represents the length of the main channel (Fig. 6.1). This governs the basin orientation, and has an integral role in the flow mechanism from different tributaries to the final outlet. It also contributes to the infiltration rate, and to the duration of the run-off between different branches with different dimensions within the basin. Thus, the following equation is used to elaborate the shape factor (Black 1991)

$$S_f = (LL_{ca})^{0.3}$$

where

L is the maximum length of the basin
L_{ca} is the distance from the center of the basin circle to its outlet

6.1.3 Width/Outlet Width Ration (Wb/Wo)

Width/outlet width ration is the ration between the maximum basin width and the width of the outlet, as shown in Fig. 6.2. If the basin width from the upstream is bigger than the outlet width, the occurrence of flood is more probable (Al Saud 2010a and 2010b). This can be attributed to the inadequate drainage capacity to carry water which is derived from the branches of the upstream area, which results in irregular flow in the drainages towards the outlet.

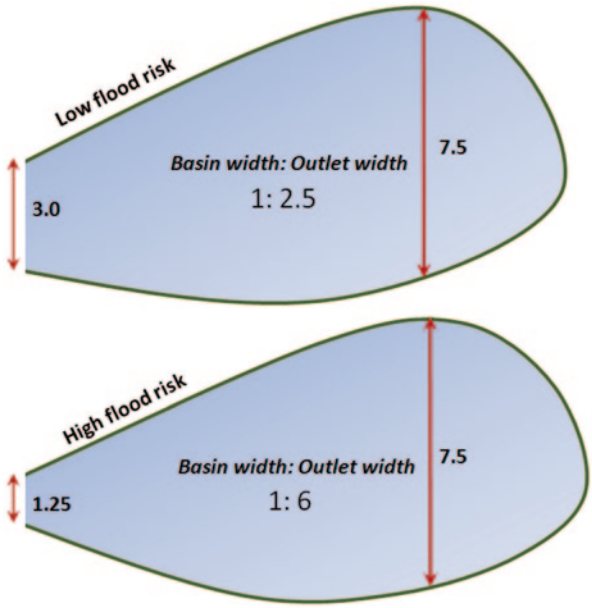

Fig. 6.2 Representative figure showing different widths of outlets in basins. (Al Saud 2010c)

The width/outlet width ration can be calculated from the application of the DEM, as mentioned previously. However, in this case we treat the basin's outer limits, regardless of the terrain features inside the basin. *Wb/Wo* ration can be simply represented by the following equation:

Wb/Wo = *Basin width/Outlet width*

6.1.3.1 Elongation Ration (R_e)

It also essential to characterize the basin's elongation, or the property of one-direction stretching with respect to its area, which describes the elongation ration. It equals 1 for a perfect circle, whilst it is zero for a straight line. According to Schumm (1956), the elongation ration equals:

$$R_e = 2 / \mathrm{L_m} (\mathrm{A} / \pi)^{0.5}$$

Where L_m is the basin length parallel to the primary watercourse, and A is the basin area, as shown in Fig. 6.3. Therefore, the elongation ration governs the flow regime at the outlet.

6.1.3.2 Circularity Ration (R_C)

Circularity ration (R_c) represents the uniformity between the external perimeter of the water basin compared to its circular form (Miller 1953).

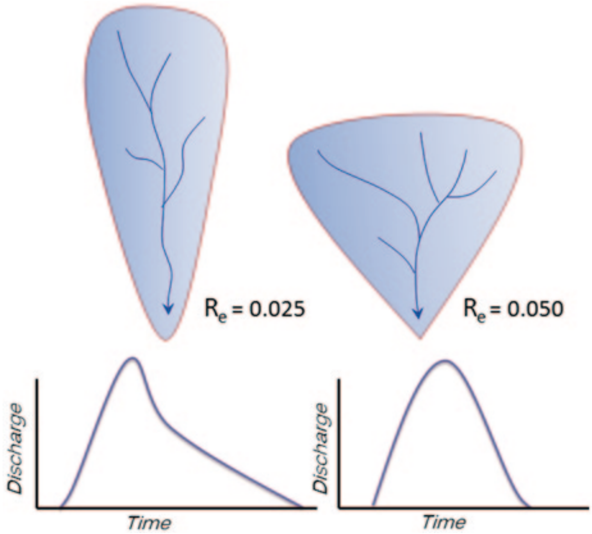

Fig. 6.3 Representation for two basins with different elongation ration

$R_c = A/A_0$

Where A_0 is the perimeter of the circle confining the basin, and A is the area of the basin.

The analysis of the principal geometric characteristics of the major water basins in the area of study, with the exception of none completed basins (joining basins) as shown in Table 6.1, shows that few of these basins are characterized by normalized effectiveness with respect to floods and torrents.

6.2 Morphometric Analysis of Drainage Systems

6.2.1 Drainage Density

Water channels may have several geometric patterns and compose a collection of natural networks on the terrain surface. However, the most important aspect of drainage distribution is the density of tributaries in a specific basin. Moreover, there can be areas with high drainage density and areas with a lower drainage density in the same basin. This is primarily due to factors related to the characteristics of the terrain. Hence, drainage density can be calculated using the following equation:

$$\frac{\sum L}{A} = \frac{\text{Total length of tributaries in particular area}}{\text{Area}}$$

Table 6.2 shows the resulting values of average drainage density in each basin, which occur in a clearly diverse way.

Table 6.1 Principal geometric characteristics of major basins as obtained from DEM

Basin No.	Basin	Length/width ratio (Lw)	Shape factor (S_f)	Width/outlet width (Wb/Wo)	Elongation ration (Re)	Circularity ration (Rc)
1	Ghouiemer	1:0.87	5.83	1:2.5	0.82	3.30
2	Om Hableen	1:20	3.88	1:1.8	0.68	1.39
4	Daghbj	1:30	4.42	1:2	0.51	1.03
5	El Hatiel	1:4.3	4.72	1:3	0.44	0.96
7	Basin # 7	1:30	3.22	1:2	0.53	0.60
8	El Assla	1:1.20	6.77	1:8.5	0.58	2.36
10	Mreikh	1:1.75	3.64	1:1.3	0.78	1.08
11	Kawes	1:3.8	5.99	1:2.57	0.38	0.85
12	Osheer	1:1.60	2.81	1:3	0.58	0.62
14	Methweb	1:2.20	5.26	1:5	0.43	0.82
15	Ghlil	1:2.15	3.45	1:2.3	0.47	0.57
17	Muwaieha	1:1.55	3.05	1:1.6	0.63	0.72
21	Abou Je'Alah	1:1.50	2.57	1:1.7	0.91	0.80
22	Al A'ayah	1:20	3.25	1:1	0.45	0.48
23	Ed-Dowikhlah	1:1.60	2.92	1:1.55	0.61	0.58
24	El-Baghdadi	1:2.20	3.34	1:1.4	0.59	0.91
25	Ketanah	1:1.70	3.78	1:2.3	0.56	0.80
27	Esh-Shoabaa	1:2.50	4.16	1:1.5	0.49	0.80
29	Da'af	1:1.75	3.58	1:1.45	0.62	0.93

Table 6.2 Average drainage density in the basins Of Jeddah and the surrounding

Basin No.	Basin	Density (Km/Km^2)	Basin No.	Basin	Density (Km/Km^2)
1	Ghouiemer	0.98	16	Selsli	0.53
2	Om Hableen	1.12	17	Muwaieha	1.02
3	Basin # 3	0.28	18	Basin # 18	1.13
4	Daghbj	0.96	19	Basin # 19	0.97
5	El Hatiel	1.36	20	Basin # 20	1.20
6	Basin # 6	041	21	Abou Je'Alah	1.53
7	Basin # 7	1.15	22	Al A'ayah	1.27
8	El Assla	1.77	23	Ed-Dowikhlah	1.24
9	Basin # 9	0.61	24	El-Baghdadi	1.14
10	Mreikh	1.76	25	Ketanah	1.25
11	Kawes	1.37	26	Basin # 26	1.23
12	Osheer	0.54	27	Esh-Shoabaa	2.20
13	Basin # 13	0.35	28	Basin # 28	1.15
14	Methweb	1.33	29	Da'af	0.95
15	Ghlil	0.85			

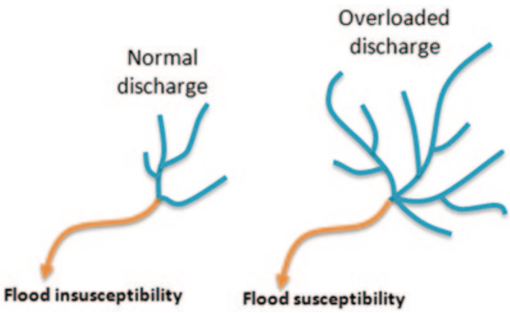

Fig. 6.4 The consistency in the number of confluences with respect to flood occurrence

The largest value is found in Esh-Shoabaa basin (i.e. 2.2 km/km^2), which is 8 times larger than the density in Basin No.3 (i.e. 0.28 km/km^2), and this reflects the importance of the morphometric characteristic in surface water flow. However, according to geomorphic concepts, the higher the drainage density, the lower the infiltration rate and vice versa. If this concept is considered with regard to the occurrence of floods and torrents, a low infiltration rate results in an increase of floods and torrents. Nevertheless, in this case there will be a non-uniform run-off in the channels. Besides, when drainage density increases, regular run-off also exists, in the opposite of region with non-uniform run-off where overland flow increases, and then enhances the flood processes.

It is also important to take into account drainage density in terms of stream confluence (i.e. number of streams joining a specific stream), which should be investigated on a local scale for a specific confluence rather than with regard to the entire basin. It was clear from the floods and torrents that occurred in the Jeddah area that the inconsistency in flow among different tributaries plays an essential role in flood occurrence. In other words, if the ration between the number of tributaries discharging to the next tributary is high, flood often occurs, while the consistency between the connected tributaries creates normal discharge (example in Fig. 6.4). This highlights the concept of "stream orders" as a significant characteristic to be diagnosed in studying floods. This will be discussed in the next section.

6.3 Streams Order

Usually, the most active factor in surface run-off occurs in relation to the channel aspects and the different existing tributaries, which in turn form a drainage network that begins with small reaches in the highest elevations, and then extends toward the end at an outlet. Hence, streams have different orders depending on their connection ration (i.e. behavior and number of connections). Therefore, the relationship between different stream orders has been considered. Small streams that start at the top of the mountains and that are connected to one side are given the 1st order appellation. The 2nd stream order is created by the junction of two or more 1st order streams, and so on for the rest of the streams.

While the process of identifying different stream orders is not the subject of this study, it is a kind of tool that helps us in analyzing the relationship between these streams, and more certainly in calculating the bifurcation ratio which is obtained from the following equation:

$$B_r = N_r / N_{r+1}$$

Where "N_r" is the number of streams for the order "r", and "N_{r+1}" is the number of streams for a next higher order.

In this study, Arc-GIS 9.3 software was used to classify streams and their specific orders (Fig. 6.5). Also, it enabled the calculation of the morphometric variables needed; all streams and their tributaries were numbered in order to make the calculations easier (Table 6.3).

6.4 Meandering Ratio (Mr)

A stream channel takes many meandering (i.e. curvature) aspects along the channel length, where several flow characteristics occur along each meander. This process depends on many geomorphological and hydrological characteristics, such as slope gradient, rock types and geological formations, among many others. It has been found that a meandering ration plays a role in the occurrence of floods and torrents, since an increase in the meandering ration decreases the flow energy and increases the stream load capacity due to the erosion process along the meandering sites. The meandering ration is calculated according to the following equation, and the results obtained with regard to the basins in the study area are shown in Table 6.4.

$$\frac{Lm}{Ls} = \frac{\text{Length of primary stream (meandered)}}{\text{Length of primary stream (straight)}}$$

6.4.1 Intersection Ration (Ir)

Usually the morphometric characteristics of drainage systems are involved in studies related to the regime of surface water flow, and several formulas and concepts are used for better analysis. However, the results obtained by these studies often differ, while some characteristics are found to be of great importance, others are given less concern. Among these characteristics is the intersection ratio (I_r), which can be obtained by identifying the intersection nodes (i.e. confluences and diversions) between different channels and branches (Al Saud 2009).

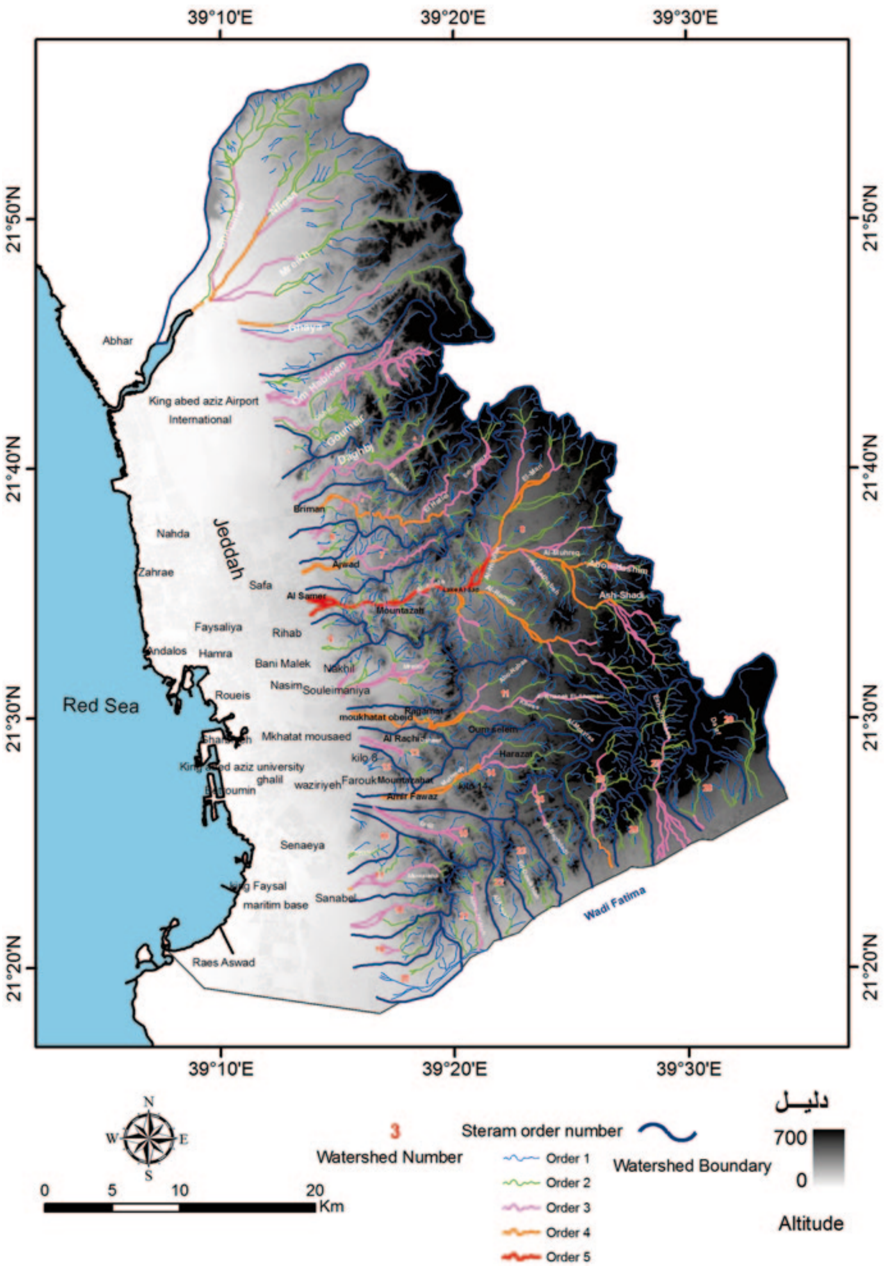

Fig. 6.5 Stream orders in the basins in Jeddah area and the surroundings

Table 6.3 Major variables for stream orders in the basins in Jeddah area and the surroundings

Basin No.	Basin	Number of stream orders					Total length (km)	Bifurcation ratio (Br)
		1	2	3	4	5		
1	Ghouiemer	107	68	15	8	–	342.7	2.64
2	Om Hableen	45	24	26	–	–	148.9	1.39
4	Daghbj	37	24	14	–	–	101.7	1.62
5	El Hatiel	73	24	16	8	–	117.5	2.18
6	Basin # 6	14	5	3	–	–	16.2	2.23
7	Basin # 7	30	10	7	3	–	51.9	2.25
8	El Assla	351	135	54	38	14	589.4	2.30
9	Basin # 9	7	7	–	–	–	12.8	1.00
10	Mreikh	31	23	14	2	–	74.9	3.33
11	Kawes	52	24	12	7	–	117.3	1.96
12	Osheer	7	7	5	–	–	20.2	1.20
14	Methweb	56	16	6	7	–	87.3	2.34
15	Ghlil	17	3	7	–	–	37.8	2.41
17	Muwaieha	17	9	13	1	–	37.9	5.19
21	Abou Je’Alah	30	11	5	–	–	45.8	2.46
22	Al A’ayah	13	6	–	–	–	25.6	2.16
23	Ed-Dowikhlah	18	10	–	–	–	29.6	1.80
24	El-Baghdadi	31	14	5	–	–	41.4	2.50
25	Ketanah	48	26	8	2	–	74.7	3.03
27	Esh-Shoabaa	55	20	25	–	–	88.1	1.77
29	Da’af	18	12	–	–	–	41.3	1.50

This characteristic indicates the degree of joining between different streams and their reaches, regardless of their length, and it is usually calculated by counting the number of intersecting nodes within a specific area, such as in one square kilometer (Table 6.4). The intersection ration represents the uniformity of connection in different streams, and the resulting uniformity in run-off; therefore, it has a function in flood occurrence. That is to say, an increased rate of intersection has a reversible proportion in flood occurrence and vice versa. Table 6.4 shows the discrepancy in the intersection ration between different basins in the study area: some basins have 25-times more increase (e.g. Basin No. 3) than other basins (e.g. Basin No.13).

Table 6.4 Meandering and intersection ratio for the basins in Jeddah area and the surrounding.

Basin No.	Basin	Meandering ratio (Mr)	Intersection Ratio (Ir) Node/km^2	Basin No.	Basin	Meandering ratio (Mr)	Intersection Ratio (Ir) km^2
1	Ghouiemer	1.05	3.2	16	Selsli	1.01	0.34
2	Om Hableen	1.35	6.3	17	Muwaieha	1.12	2.4
3	Basin # 3	1.18	70	18	Basin 18	1.12	1.61
4	Daghbj	1.31	6.1	19	Basin 19	1.05	1.15
5	El Hatiel	1.02	5.5	20	Basin 20	1.12	1.04
6	Basin # 6	1.01	0.8	21	Abou Je'Alah	1.19	4.6
7	Basin # 7	1.04	1.2	22	Al A'ayah	1.17	2.04
8	El Assla	1.27	7.6	23	Ed-Dowikhlah	1.20	1.92
9	Basin # 9	1.10	2.4	24	El-Baghdadi	1.14	1.80
10	Mreikh	1.23	2.6	25	Ketanah	1.23	3.61
11	Kawes	1.28	3.1	26	Basin # 26	1.12	2.03
12	Osheer	1.19	0.53	27	Esh-Shoabaa	1.27	5.8
13	Basin # 13	1.03	0.26	28	Basin # 28	1.17	1.17
14	Methweb	1.17	3.4	29	Da'af	1.20	2.11
15	Ghlil	1.14	1.9				

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Chapter 7
Data Analysis and Manipulation

Abstract In data analysis many methodologies are applied for the assessment of floods and torrents. These methodologies vary according to data availability and tools. Recently, the introduction of space observations and geo-information systems has provided valuable information as a result of the integration of different physical and anthropogenic aspects retrieved from satellite images and field surveys. This means that the factors that influence floods and torrents can be correlated. In particular, these new findings have helped in determining the major causes of the catastrophic flood events in Jeddah during 2009 and 2011.

This study is based mainly on the analysis and integration of several major components in the occurrence of floods and torrents. As previously stated, it treats all the available data and information which has been acquired to date. This chapter analyzes and manipulates this data and information, and deals with: rainfall and flood probability, the general geomorphic shape of the flood area, hydrometric, geometric, and morphometric analysis of the drainage systems, as well as the impact of urban expansion on the occurrence of floods and torrents.

7.1 Rainfall and Floods

Rainfall is considered to be the generating factor of floods and torrents. Without heavy and torrential rainfall there would be no floods. Thus it is necessary to focus on this factor when investigating the flood process. Rainfall can be studied for the early warning and forecasting of flood disaster. Usually, meteorological conditions follow specific regimes, which are generally familiar to local experts and concerned institutions, as well as to local inhabitants. However, when knowledge is lacking or insufficient data are available, no inducement or prediction can be made.

According to the estimates of the General Corporation for Forecasting and Environmental Protection (GCFEP) in Saudi Arabia, in November 2009 rainfall in the Jeddah area was about 95 mm over the space of two of hours, while in January 2011 it reached about 120 mm over a similar time period in the same area. These rates can be compared with those retrieved from space data, and also from the Tropical

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Rainfall Mapping Mission (TRMM). Therefore, the geographic distribution of the rain can be determined as shown in Fig. 3.3. However, there are not enough climatic stations in the area of study to provide us with a comprehensive picture of overall rainfall patterns and trends. For this purpose, many climatic observers in regions worldwide now depend on meteorological monitoring systems; by following systematic procedures they can predict climatic behavior, which enables them to implement appropriate protective measures.

It is evident that the study area has lately witnessed a number of rainfall peaks, that is, a relatively large volume of precipitation over a short time period. Available climatic data show that the area had not witnessed such rainfall peaks for 27 years, in some cases for more than several decades, and this may be attributed to the new climatic conditions that now exist.

The major causes of the changing climatic conditions in the area of Jeddah are still undefined, and while there has been no credible study of this issue, there are correlations that can be made with some existing global models and scenarios. The focus of the present study, however, is not the specialized analysis of climatic conditions, although it is concerned with the geographic distribution of rainfall and its correlation to floods.

Based on the available records and space observations (i.e. TRMM system), and the results obtained from field investigation, however, the following can be concluded:

1. The area is witnessing a climatic cycle, which indicates the recurrence of meteorological events at regular time intervals, although this needs to be proved by long-term climate data. Several regions in the Middle East and also in the Mediterranean basin are known to have climatic cycles, notably those located in the humid zones. It is assumed that some of these cycles run over three decades and that others run over a century.
2. Many researchers have attributed these changes to worldwide global climate change, and as indicated by the IPCC (2007), the Arabian Peninsula is expected to have an estimated 30 % increase in rainfall rate over the next few years. In the light of these findings, a correlation can be made between global climate change and climatic cycles and their occurrence. The vast paleo-drainages that are evident in the Arabian Peninsula indicate the heavy rainfall and climatic fluctuations that have occurred in the past.
3. The exacerbation of torrential rainfall that the area has witnessed in the last few years indicates that it may be due to a new and particular factor. Modis satellite images obtained on a periodical basis show the recurrence of smoke and cloud masses extending along the coastal zone adjacent to the Jeddah area. The fact that no such smoke trends have been observed from the west means that they are locally produced, most probably by the many industrial and petroleum activities that take place in the region.

When these clouds accumulate and when there is increased temperature and pressure, they condense at certain levels in the atmosphere. Western and south-western winds in the area push the clouds eastward unless they are restricted by the elevated mountain chains, which act as a climatic barrier, to the east of the Jeddah area. The smoke-formed clouds are expected to precipitate as torrential rainfall, as happened in November 2009 and January 2011.

By gathering data on the rate and distribution of rainfall, as well as its coincidence with the geographic distribution of floods and torrents, and by interrelating these data with the magnitude of damage resulted after the rainfall peak (95 mm and 120 mm), it is feasible to induce a description of the relationship between rainfall peaks and levels of flood damage (Fig. 7.1).

The trending curve in Fig. 7.1 shows the direct proportionality between the increase in rainfall rate and the five damage levels according to filed observations and satellite image analysis. Thus, it is expected that when the rainfall rate reaches 75 mm, a flood of level 3 will occur. At this level, negative impact is predicted, giving rise to floods and torrents. This indicates that a rainfall rate of 100 mm within a couple of hours may result in a catastrophic climatic event. However, it must be added that mitigation can occur which may affect the trending curve shown in Fig. 7.1. In addition, it must be pointed out that the increase in rainfall rate is an exponential variable. This means that the increase in the rainfall rate becomes more damaging at a higher level than the same increase at the lower levels. For example, a 10 mm increase in a rainfall rate on 100 mm has much more effect than a 10 mm increase on 50 mm. This is why the trend in Fig. 7.1 indicates increasing damage in line with the increase of rainfall rates.

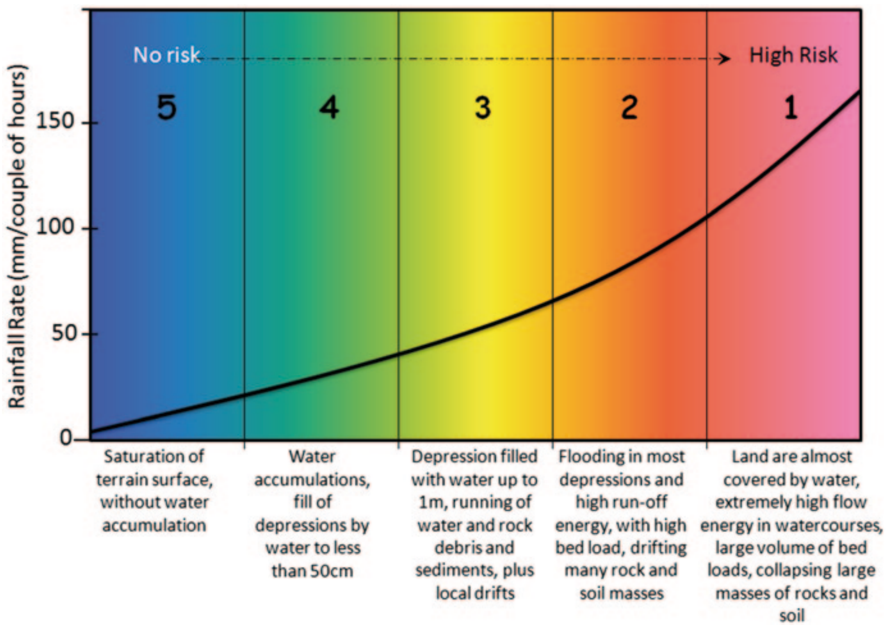

Fig. 7.1 Schematic figure showing the relationship between rainfall rate and flood levels

7.2 Geomorphologic Shape of Terrain and Water Flow

Usually, areas at natural risk are viewed via comprehensive observation, notably after the event (e.g. flood) has taken place. This can be done by using space observations, which give a picture of whole terrain signatures and help in identifying the elements which give rise to the occurrence of natural disasters. It is this approach that has recently been used to assess the damage caused by such disasters and to increase the knowledge of their causes, neither of which could be done by earlier methods (Jiren 2005; Mertz et al. 2010).

From the satellite images that were processed in this study, and supported by the DEMs, we have established that two major terrain basins cover almost the entire region and that they are separated by rocky hills. One is the rocky basin, as identified in the study by Al Saud (2010c), while the other is the flattened basin which is located to the north of the first one. Each of these basins is characterized by particular geomorphologic and hydrologic elements, and thus each has a different flow regime.

According to the analyzed major elements in DEMs, the rocky basin represents a semi-closed and concave-down terrain, and it is mainly situated between the faulting systems of Wadi Fatima and Wadi Al-Bayada to the south and east, and bounded by the mountain chains of Jabal Abou Jinad and Jabal Abou Rokaieba to the north (Fig. 7.2).

These terrain basins, which cover large areas, encompass a number of basins (i.e. major, minor and joining ones). Their outlets open towards Jeddah city to the west and Wadi Fatima to the south. These geomorphologic units (i.e. terrain basins) can be considered important elements in flood occurrence if each basin is viewed as a unique hydrologic system. The concavity of the rock basin downward in the terrain

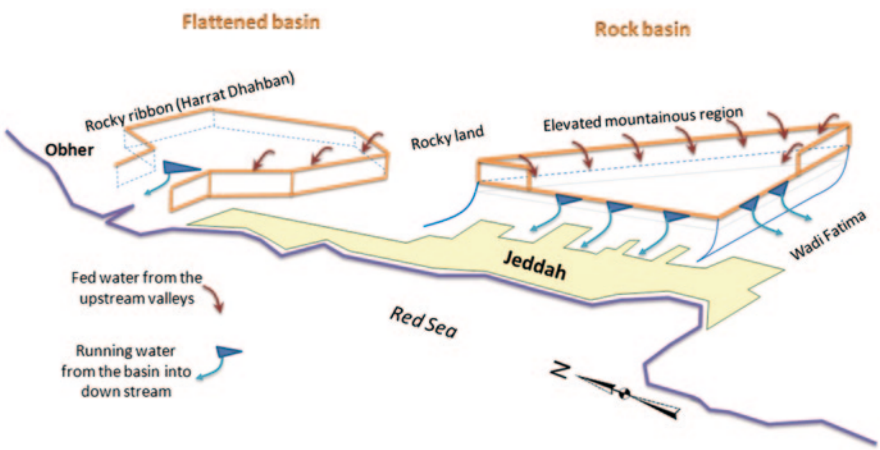

Fig. 7.2 Schematic figure showing the general geomorphologic shapes of terrain in Jeddah area and the surroundings

body and the existence of surrounding elevated regions, which capture water in a number of streams, result in a high volume towards the mouth of the basin. The level of water continues to rise in the basins unless it becomes saturated, and then starts to overflow westward to the coastal zone of Jeddah, and southward towards Wadi Fatima, as was the case in November 2009.

Despite the fact that the flattened basin is located adjacent to the rocky basin, it is different from a geomorphologic point of view and controlled by the geologic structures that exist in the area. It is also surrounded by the thin mountain ribbon of Basalt (Harat Dhahban), which extends to form a fence-like shape, inside of which water accumulates and then outlets into Obhor bay. This basin comprises mainly a plain region (Fig. 7.2).

According to the shaping of these two basins, they can be diagnosed with respect to floods as follows:

1. *The Rocky Basin:*

- The downward-concavity makes it a suitable area for water accumulation, and water flow starts above the saturation level. This flow mostly takes place in valleys to compose a run-off or flow on terrain surface resulting in non-uniform overland flow.
- The presence of numerous valleys within the basin results in a large volume of water discharge together at the same time. Most of these valleys are long and wide enough to bear a huge amount of water.

2. *The Flattened Basin*:

- Since the mountain chains around this basin compose a thin geomorphologic ribbon with a negligible area of sloping terrain from the mountain peaks, this ribbon works mainly to restrict rainwater rather than capture water, which is the case in the rocky basin. In addition, this basin has fewer valleys than the rocky basin, and thus accumulates less water from the elevated regions.
- Since the outlet (basin mouth) of this basin is relatively large, it is not anticipated that rainwater will accumulate at identified outlets, but rather that it will run toward the sea at Obher bay. According to the above analysis and from a comprehensive observational point of view, the rocky basin is susceptible to water accumulation and flow, with a great many sites susceptible to floods in the confined and depressed areas. This was indicated from field observations and processed satellite images (Fig. 4.4).

Generally speaking, the flattened basin has a moderate susceptibility to flooding according to its geomorphologic setting. This means that the northern part of the study area is less vulnerable to floods and torrents in comparison with the southern part, and this was also evident from the analysis of satellite images (Fig. 4.4).

7.3 Geometric Analysis of Basins and Water Flow Regime

As well as identifying geometric variables, the object of this analysis is to assess the influence of the geometric characteristics of water basins in the area of concern, these being composed of hydrologic units located in the rocky and flattened terrain basins. This in turn enables the assessment of the impact of the geometric dimensions of a basin in the occurrence of floods and torrents.

Normally, two approaches are employed to classify areas at risk of floods and torrents. These are as follows:

1. Classifying each water basin as a separate hydrologic system based on the geometry of the catchment area and the morphometry characteristics of the existing valleys. These characteristics were discussed in Chap. 6. In this case, the susceptibility of a basin to floods and torrents is determined separately for each basin (Fig. 7.3a).
2. Classifying zones at risk of floods and torrents in the entire region including all basins. This classification is mainly based on the integration of several influencing factors, thus a number of zones will appear to be at various levels of risk to floods and torrents (Fig. 7.3b). These factors will be modeled further in Chap. 8.

Accordingly, the effectiveness of physical characteristics and their various drainage systems can be analyzed. This can be induced schematically in the GIS system, where DEMs can play an integral role. In addition, it was noted from this study that the advanced techniques and analytical tools entailed by the use of DEMs are

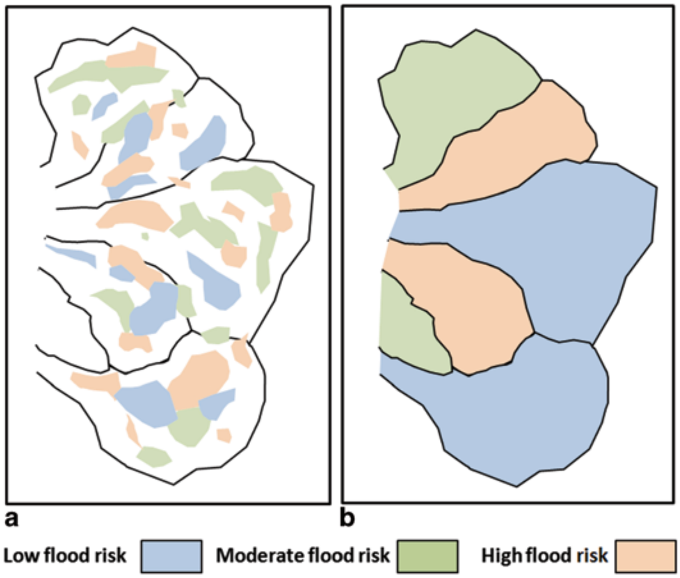

Fig. 7.3 Examples on the used methods to classify flood risk zones. **a.** According to flood zones, **b.** According to basin boundary

helpful in diagnosing geometric variables, which are usually difficult to obtain by other methods.

It is clear from the data analysis in Table 6.1 that many basins in the area (e.g. basins No. 12 and No. 19) are characterized by moderate susceptibility to floods and torrents in terms of their geometric characteristics. Even though some variables show high impact value on the occurrence of floods and torrents, the overall result may be low or moderate susceptibility, and this can be attributed to the integration of different variables. For example, Wadi El Hatiel shows high values of length/width ration (1:4.3), as well as circularity ration (0.96); however, the overall result shows a moderate susceptibility to the occurrence of floods and torrents. The same applies to Wadi Kawes, which has high values for these variables (1:3.8 & 0.85), but has a low susceptibility to the occurrence of floods and torrents.

There are some basins such as Ghouiemer which have a remarkably high elongation ration (0.82) and circularity ration (3.30). The same is true for the El Assla basin which has a high length/width ration (1:8.5). In some other basins, there are significant differences in the values between variables, such as Abou Je'Alah, which has low value in the shape factor (2.57), and high value in the elongation ration (0.91). All of these values are indicative elements of the basin's effectiveness against the occurrence of floods and torrents, as shown in Table 6.1.

While these characteristics cannot be considered on their own as a major cause of floods and torrents, they are among many integrated factors that act on the hydrologic process of flooding. This is the reason why some basins were not subject to damage even though their geometric characteristics were effective, while other basins were. This can also be attributed to the fact that some of these characteristics might be more effective in some regions than others in the same basin (downstream for example), which might in turn be due to patterns of urban settlement, as in the case of the Kawes, Osheer and Methweb basins, which show low propensity to floods and torrents from the geometric aspect, but were nonetheless severely damaged by recent flood events. Therefore, geometric characteristics can be utilized in order to assess the impact of human activity on floods for each basin alone, as well as in prioritizing the implementations to be applied for the requisite flood controls.

7.4 Morphometric Analysis and Flow Mechanism

The shapes and orientation of streams, their patterns of joining and also their dimensions, represent the morphometric characteristics which play a role in the mechanism of floods and torrents. However, for an ordinary stream, without any human interference, flood probability is almost negligible and if flood occurs, it will be at the minimal level. This is because the streams (valleys) have detached from their passageways frequently over their geological history and their flood plains have become wide enough to capture any flood water that might have existed, and thus they are adapted to any changing hydrologic processes that might occur. This is well pronounced in mature streams where water outlets become uniform under all climatic conditions. These streams, with their uniform outlets, will discharge their bed loads into a definite place (e.g. lake, sea, etc). This is exactly what streams have done in the area of Jeddah for thousands of years, as is well indicated by the pronounced geomorphological features along the western coast of Saudi Arabia, such as terrain portions discharged into the sea, bays, marshes, delta and thick sedimentation sequences. All of these features are attributed to ancient water flow systems and their outlets as they existed under different climatic conditions when water was discharged uniformly into seawater with no constraints on its flow (Al Saud 2007).

According to the morphometric analysis of the area of study, in combination with a number of geomorphic concepts, drainage density is found to be differentially distributed among the basins therein, but much attention must be paid to the consistency between the numbers of the connected tributaries that create normal discharge. Even though this property (i.e. consistency in the number of connected streams) is largely local, it interacts with the stream order property and the bifurcation ration, which was calculated for each basin in Chap. 6. However, some basins have five stream orders, such as El-Assla basin, which was subject to severe flood damage. This might be an indicator of different physical characteristics that influence the uniform water flow.

In this study, essential morphometric formulas were applied. These include the meandering ration and intersection ration, both of which have an important impact on the occurrence of floods and torrents. It was obvious that there is a direct proportionality between the least meandering ration and flood occurrence. Also, it was found that the increased intersection ration in some localities is consistent with the drainage density in the same localities, which are again related to the consistency between the connected tributaries. All of these formulas are essential for the engineering practices that come into play when applying flood control mechanisms.

The morphometric characteristics of drainage systems can provide more accurate information if they are treated on a local scale. There are several morphometric elements which act in creating floods and torrents, as happens in localities where streams are connected, notably streams which contain thick sediment. These streams accumulate all the loaded sediment when they are connected, and when their capacity is overloaded, floods occur. Such was the case in Wadis of El-Hofna, Abou Nabaa, AlMohreq and Kawes.

The analysis of morphometric characteristics of existing drainage systems in the study area was discussed in Chap. 6. In contrast to the case of geometric characteristics, it was evident that there is a consistency in the effectiveness of different variables with regard to the occurrence of floods and torrents. For example, Abou Je'Alah basin is characterized by relatively high drainage density (i.e. 1.53 km/km^2), which is consistent with bifurcation ration (i.e. 2.46), as well as with the intersection ration (i.e. 4.6 node/km^2). This consistency reflects the interrelation between the different characteristics of existing streams, which have an essential role in water flow regime.

In addition to morphometric characteristics, there is another important and remarkable phenomenon that exists in the area of study, which distinguishes it from other areas along the western coast of Saudi Arabia. This phenomenon is represented

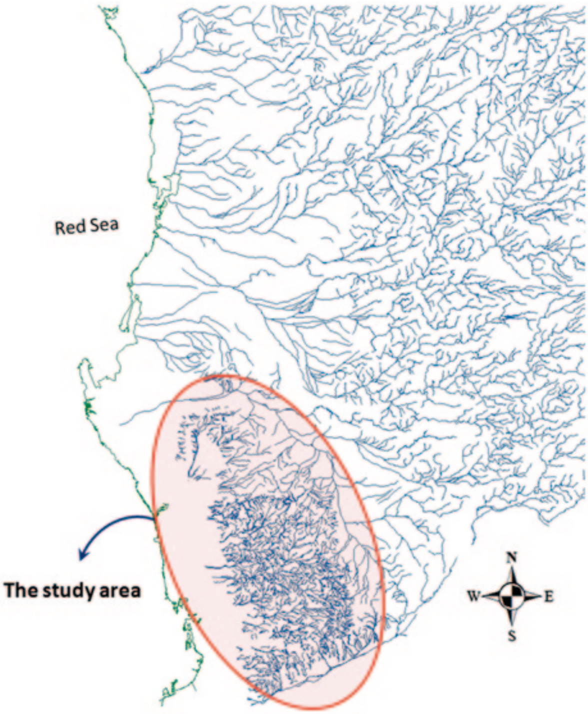

Fig. 7.4 Crowded drainage systems of the study area with respect to the surrounding areas

by "Crowded" drainage systems, which compose a sort of compressed drainage system with respect to the surrounding drainages. This might be attributed to tectonic activity that has resulted in crowded streams and catchment areas (Fig. 7.4).

The existence of this crowded drainage system can be correlated with the reasons behind the floods that have occurred. It is evident that the level of squeezing is concentrated in the rocky basin, where the damage that resulted from floods and torrents was severe, thus indicating the effectiveness of this phenomenon in the event of such natural hazards.

7.5 Geographic Distribution of Floods

When flood occurs, the regime and power of water flow determines the level of damage. Water running outside of its regular passageway usually results in destruction in the surrounding areas. Rainfall in itself, when it has no remarkable movement, often accumulates at specific sites without causing any damage and will not impact the surrounding areas, whereas running water can have serious amounts of impact depending on the region. The fact that running water can dislodge and transport objects that stand in its way can seriously increase its negative impact.

The geographic distribution of bodies of water and their dynamic movement were identified by satellite observations and field verification, and then classified into two major categories. These are: moveable water (Dynamic) and accumulated water (Static). These two categories are related to several physical and anthropogenic parameters. They can be diagnosed as follows:

1. *Moveable water*

This refers to water which runs on the terrain surface as a result of slope gradient, or due to an overloaded mixture of water and sediments, and in some instances it is attributed to the narrowness of the valley in which it runs. This water is usually formed in elongated orientation according to the valley shape (Fig. 4.4). In the study area, the category of moveable water was estimated at 89.6 km^2, which is equivalent to about 63.7 % of the total damaged areas. In this case, wide valleys are found to be more dangerous due to the presence of sediments and sand, in addition to dense human settlements.

Observations regarding this category show a sudden termination of water flow (i.e. flow cut) in many localities; this was noticed at the contact between running water and urban settlements. Flood damage in these localities was severe.

2. *Accumulated water*

This refers to water that accumulates directly from rainfall and shows no obvious movement, or that sometimes exhibits a restricted flow that does not exceed a few meters (Fig. 4.4). The area where this category of water exists in the study area was estimated at 51.05 km^2. Usually, the flooding of such water does no remarkable damage apart from the denudation of localities, which may have an adverse environmental impact and result in epidemics.

Figure 4.4 shows that the main distribution of floods and torrents is concentrated in the middle-eastern part of the study area, where water runs along valley courses In addition, floods and torrents have occurred in some of the northern valleys, but have had less impact due to the relatively narrow cross-sections of many of the existing valleys. This type of accumulated water is found at a large number of sites (i.e. polygons) with different scales (areas). There are 8223 sites where this type of accumulated water has been recognized by satellite images.

7.6 Urban Expansion and Floods in Jeddah City

Urban planning can play a major role in reducing the damage caused by floods if the risk of such events is taken into account in the construction of buildings and roads. Such practice is often followed in developed countries where legislation is enforced in this respect. While urban expansion itself can be a negative factor if it is not consistent with engineering parameters that consider the various natural risks that may arise at any time, this is not necessarily the case when the expansion is well planned.

Sometimes, an excess of water can be harmful rather than beneficial. The negative effect of human interference with nature has been observed in Jeddah City and its surroundings. Such interference contributes not only to the risk of floods and torrents, but also to other environmental problems. This has been clearly observed by a field reconnaissance of the area. There may be several reasons behind this uncontrolled interference, but human safety and the protection of natural resources should remain of the utmost importance.

It was clear from this study that the geographic distribution of human settlements has increased, and that the increase has been eight times during the last 35 years. This has been accompanied by an increase in population size. Recent statistics show that population growth in Jeddah City ranges between 20 and 28 %, which exceeds the international population growth rate 15 times (i.e. 1.5−2 %). The major reason for the increase in the population is considered to be the large number of people who make Pilgrim and Omra tasks, and some of them stay in the city even after they finish these tasks. Moreover, the population has expanded in neighboring regions, to the east rather than the north. This is due to the fact that the Abdulaziz International Airport is located in the eastern region, and also due to the high cost of land in the northern region. With regards to the area south of Jeddah, this is a very dry region which is covered by sand dunes, which limits urban expansion there.

On the other hand, the eastern region of Jeddah is mainly mountainous and enjoys a mild climate, which attracts people to settle there.

From a demographic perspective, urban expansion east of Jeddah City has dramatically increased. These new settlements disrupt the natural routes of rivers through valleys to the sea, and this is a major cause of floods and torrents.

Apart from some minor valleys located in the south of the study area all existing valley outlets have been closed as a result of urban settlement in different areas (Fig. 7.5). Urban settlement in the valleys involves, in many instances, a good deal

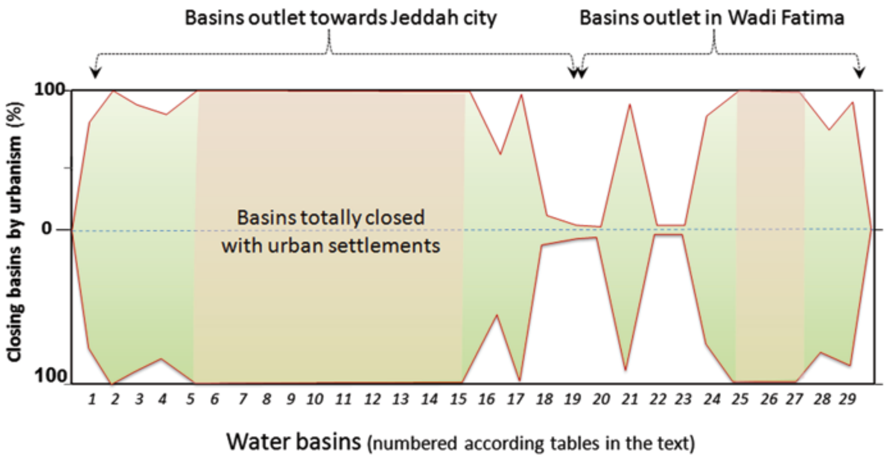

Fig. 7.5 Percentage of basins closeness to urbanism in Jeddah areas

of construction and building. As mentioned in Fig. 7.5, the term ‘closed basins’ is used to describe the location of these settlements, to refer to the fact that the primary water course and flood plains areas have been closed. The expansion of human settlement in valley courses blocks the major geomorphic elements that play a role in the run-off process, and this may result in the extinction of many watercourses. This creates a difficulty in applying geometric and morphomteric formulas to these basins.

Moreover, there are dense human settlements in the basin territories themselves, where the percentage of these territories in relation to the entire basin area ranges between 65–95 % in some cases, such as in the middle basins adjacent to Jeddah City (e.g. basins No. 9 and 14). In these basins, urban growth is taking place at a tremendous rate and shows no sign of abating.

Urban expansion in the area of study has many far-reaching effects. In some cases, it falls foul of existing laws and legislation and does not take environmental factors into account. The most common aspects of urban expansion in valley courses in the study area (Fig. 7.6), as evidenced from field observations, can be summarized as follows:

1. Large-scale human settlements or individual buildings, and the services that accompany these urban areas (e.g. fuel stations, shops, etc).
2. Construction of roads in valley passageways or parallel to valley courses.
3. Planned areas that are bordered by fences and roads.

Fig. 7.6 Examples from Jeddah area showing different aspects of urban expansion in valley courses

4. Commercial real estate areas that are bordered by dumped sediment or rubble.
5. Electrical and water supply lines directly through valley courses.
6. A miscellany of industrial activities (e.g. factories, workshops, etc).

It can be concluded that if these valley courses were left open to the sea, floods would be less likely to occur or they would have less impact. The construction of human settlements in these valleys blocks the natural passageways of water, which results in an increase in water levels unless the water invades the flood plains, and then floods occur. In addition, the accumulated power of the water dislodges objects located in valleys and sets them adrift, as happened in the Harrazat, Kowayza and El-Masaad areas.

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Chapter 8
Data Modeling for Floods and Torrents Assessment

Abstract There are several factors that influence the occurrence of floods and torrents, and thus their impact on humans and the environment. These factors vary between regions, and their influence is diverse. In order to integrate them, according to their levels of impact, a systematic moulding must be applied. In this study, levels of impact were induced from the flood events that occurred in Jeddah during 2009 and 2011. An empirical molding approach was taken, the creditability of which was confirmed from space observations and in the field verification.

Based on the various data and information obtained, this study examined aspects related to the floods and torrents that took place in Jeddah City and its surroundings. These included rainfall distribution, urban expansion, damaged areas and influencing factors. The study applied comparative analysis to different regions that share similar physical characteristics, and analyzed satellite images acquired at different dates to assess the extent and mechanism of the damage. In such a study, it is vital to investigate the method of data analysis and correlation between various datasets with the actual physical terrain. In this way reliable results can be obtained and a comprehensive picture of the events that occurred can be gained. Knowledge of the factors that influenced these catastrophes enables the proposal of an integrated management approach towards flood mitigation and prevention.

Several factors act in the process of floods and torrents, and they have different levels of effectiveness. This information was induced from data analysis, the results of which were integrated with space observations of the events that took place in 2009 and 2011, and also confirmed by field verification.

The usual method of procedure is to map the zones at risk of natural hazards. This is done by modeling a number of influencing factors that act in the occurrence of catastrophic events. The next step is to integrate (i.e. systematically superimpose) these factors followed by electronic manipulation in the GIS systems. This will reveal areas of specific effectiveness that represent the risk zones. In other words, the hypotheses need to be calibrated with the existent state of things on the ground. The hypotheses are represented by the factor acting on the event, while the existent state is the damaged areas on the terrain surface.

However, in this study, the damaged areas had already been identified after the two flood events of November 2009 and January 2011; this was accomplished by

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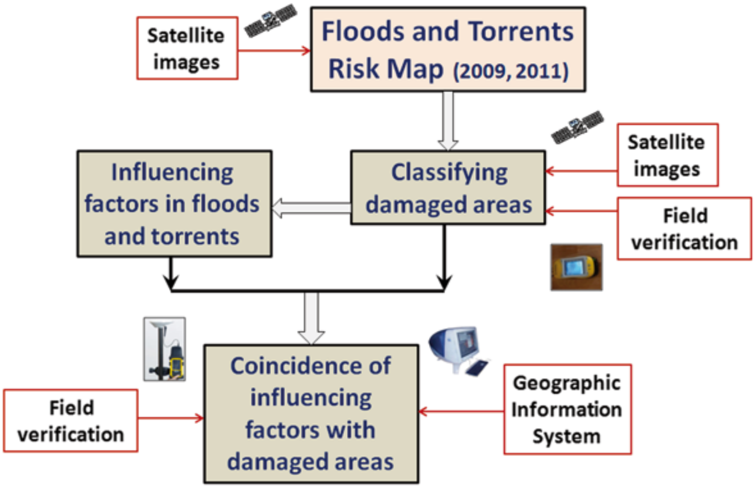

Fig. 8.1 A scheme for data modeling to induce the effectiveness of the influencing factors mapping flood risk zones in Jeddah area

the observation of different satellite images. As a result, the risk zones are now well recognized, and so the task is to compare the localities of these zones with the existing factors in order to determine the degree of effectiveness of these factors in the occurrence of the event. Also, masking the impact of the anthropogenic factors will enable mapping zones at the risk of natural hazard.

This chapter will describe an empirical method for data modeling that considers the geographic distribution of damaged areas. In addition, the levels of damage will be classified in order to induce their consistency with the influencing factors in floods and torrents (Fig. 8.1).

8.1 Floods and Torrents Map of Jeddah Area

In Chap. 4, data and information on water flow and accumulation on the terrain surface were discussed, and different aspects of the phenomena were considered. There was a difference in the geographic distribution of floods and torrents in each event (i.e. 2009 and 2011), which was attributed to several controlling factors, such as the diverse distribution of rainfall. Also, as mentioned previously, there was a clear overlap between the geographic distribution of rainfall in both cases, which makes it possible to consider rainfall as a constant factor.

Accordingly, the damaged areas in both cases, which are estimated at about 140.65 km^2 if the events of 2009 and 2011 are combined, are anticipated to extend in relation to the increase in the geographic distribution of rainfall (according to Fig. 7.1). The extent may also be exacerbated by the increase in urban expansion, especially in critical zones such as watercourses. However, the areas at risk of damage can be reduced if appropriate protective measures are implemented to control water flow, water storage and the uniformity of discharge.

The processing of high-resolution satellite images, some of which were about 50 cm spatial resolutions, enabled the observation of each patch of water on the terrain surface. It was discovered that the study area (1947 km^2) included more than 10,400 patches of water accumulation with different shapes and along routes of water flow, which were of various scales and aspects. It is natural that water runs off along valley courses and accumulates in depressions and low-lands, but the greatest damage was found in areas where obstacles exist, and it was more severe than was anticipated. This evidenced that human interference in the area of study is affecting the possibility of floods. The flood damage map was directly obtained from satellite images which were acquired at various dates and then overlapped so as to have large areal coverage as in Fig. 4.4 This may then be coincided with information that will be obtained from the integration of different factors, if these factors are modeled properly. For example, the flood risk map, which was produced by the author for part of the study area, corresponded with the geographic distribution of the floods and torrents of 2009 (Al-Saud 2010c).

8.2 Damaged Areas from Floods and Torrents

The extent of damage was different in each phase of study, whether in terms of the areal extent of the damaged areas or its impact on humans and the environment. As mentioned before, the extent of damage mainly depends on the distribution and rate of rainfall, in addition to physical and anthropogenic factors and whether protection controls exist. Damaged areas were identified from satellite images and field surveys, and it was clear that the invasion of water, especially when it was dynamic, resulted in casualties and deaths in many localities. Moreover, some villages such as Harrazat and Bahrat El-Mojahdeen were totally destroyed. Other damages were represented only by water accumulations. Also, satellite images showed that the damaged areas were totally or partially covered by water and were sometimes subject to the impact of drifting sediment and rock debris.

8.2.1 Field Verification

The field surveyis an integral part of the studies that employ remotely sensed techniques, and is used to verify the reliability of findings and observations on satellite images. Thus, field verification confirms the creditability of the method of analysis that has been followed. In the present study, field surveys were carried out over two time periods; one after the flood event of 2009 and the second after the flood of 2011. Field verification was accomplished by visiting the hotspots and all sites where floods and torrents occurred. The aim of field verification is to:

Fig. 8.2 Mud cracks, as traces of accumulated water from floods and torrents, which were previously identified by satellite images

1. Confirm the reliability of geo-spatial data and information about floods and torrents which were extracted using space technology.
2. Investigate damaged localities of different scales and identify (with the help of the inhabitants) the local elements related to floods and torrents, as well as consult historical records of floods in the area
3. Measure the vertical dimensions of the damage, such as the depth of drifted land masses and the thickness of sediments, which are tedious to calculate from satellite images.
4. Investigate the existing protective mechanisms and works in progress, especially those located in valley courses.

Topographic maps were used during the field survey, notably to identify the names of different areas and valleys. In addition, thematic maps and processed satellite images were utilized. The geographic coordinates for localities of concern were measured using GPS. Although the dates of field verification were not consistent with the dates of retrieved satellite images, the traces and indicators of flood and torrent sites were accurately induced (example in Fig. 8.2).

In the field verification for the flood of 2009, 63 major localities where damage was incurred were identified from satellite images (according to the flood risk map of 2009, Fig. 4.1). In the field verification for the flood of 2011, 74 localities were investigated after the event took place. The selection of localities was based on the recently produced flood risk map of Jeddah (Fig. 4.4).

8.2.2 Damage Classification

There are three principal categories that are applied to damage levels: high, moderate and low (Fig. 8.3). These classifications take into account the areas, aspects and mechanisms of damage, as well as its impact. The extent of damage was identified through field verification. The categories can be diagnosed as follows:

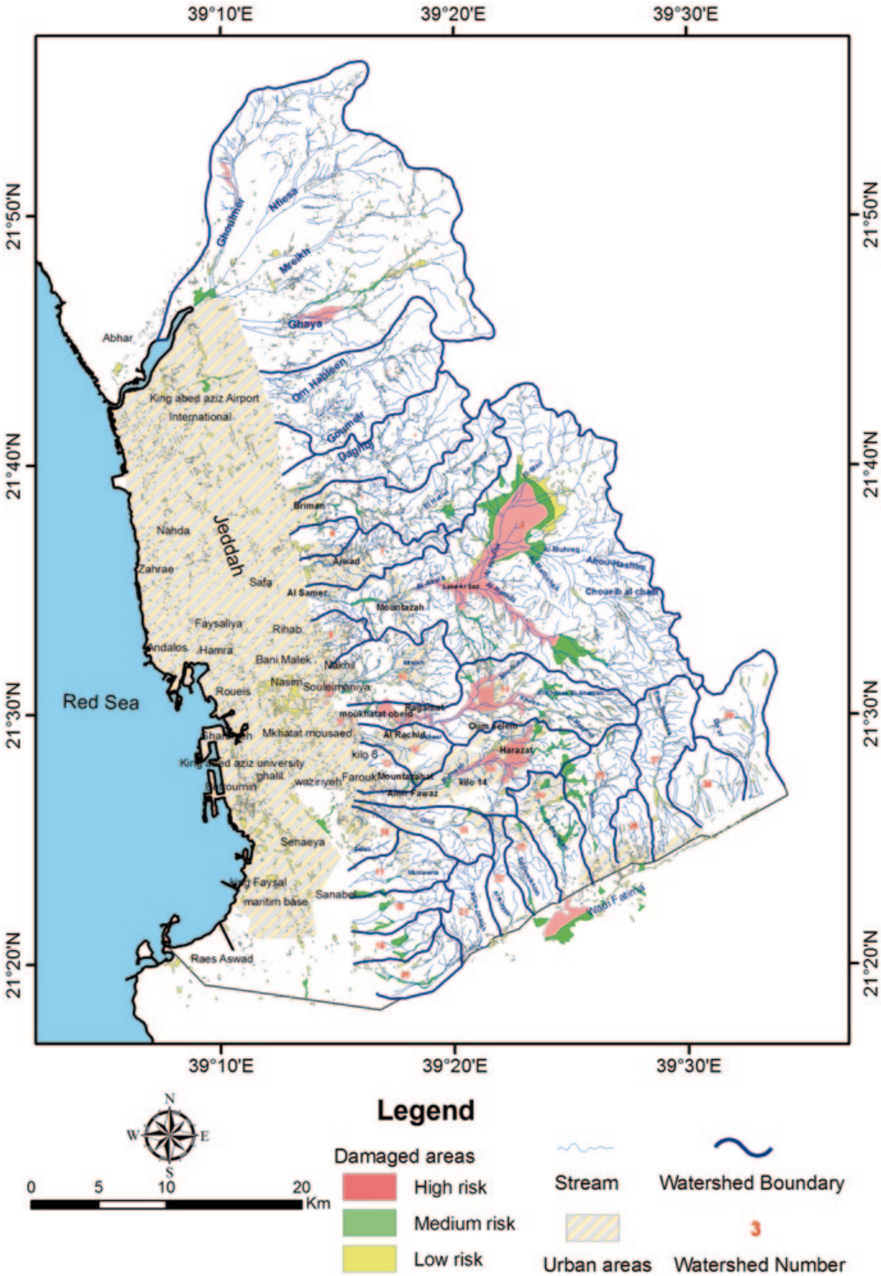

Fig. 8.3 Major categories of the damaged zones by floods and torrents

1. High damage level

This damage level covered an area of about 44.72 km^2, which is equivalent to about 2.29 % of the studied area. It includes localities invaded by running water with heavy bed loads of sediment which can reach up to 1 m thick in some places. The high flow energy of the water means that it can dislodge and carry any object or material in its way. This type of water is mostly represented in valley courses, channels and roads. It can result in the massive destruction of buildings and can also cause landslides due to collapsed rocks and soil. The mechanism of distribution of this damage aspect is often linked to the direction of the transported sediments and injected water.

2. Moderate damage

This damage level covered an area of about 38.64 km^2which is equivalent to about 1.98 % of the studied area. It includes localities that have short-distance running water, such as small valleys, where the water is accompanied by small-scale drifts (i.e. less than a few hundred square meters) and causes limited damage. This category of damage aspect follows a similar aspect to that of transported water and sediments, and it sometimes follows the aspect of restricted water described in Chap. 4, Sect. 4.4.

3. Low damage

This covered an area of about 57.29 km^2 which is equivalent to about 2.94 % of the studied area. The water here has no or a negligible flow, and at shallow depth does not exceed 25 cm. It may be accompanied by local drifts along the edges of roads, and water accumulations are surrounded by mud. This water has limited impact on the environment or on humans. The water distribution mechanism follows that of restricted and accumulated water types, as well as that of water that runs in roads and urban areas.

The resulting map, which shows the geographic distribution of damaged zones, reveals that some localities were severely damaged by floods and torrents. Urban settlements are rare in these localities, meaning that the damages only affected the environment. In other instances, some localities have been subject to moderate or low floods and torrents, but the presence of human settlements has increased the degree of damage. In this study, both cases were investigated in the field assessment.

In order to verify the reliability of data extracted from satellite images, the obtained results were accompanied by field verification; however, statistical comparative analysis could also be used. For the results obtained in the first phase (i.e. flood 2009), a *Simple linear regression* approach was applied, since this can illustrate different mathematical variables. Following this, all variables for the 63 localities, were treated. It was concluded from the illustrated curve that the "Correlation coefficient", symbolized as "R^2" is 0.87, which is a positive indicator confirming the reliability between the comparative variables extracted from satellite images and from field verification.

In the second phase (i.e. flood 2011), damages were classified into three categories (i.e. high, moderate and low) as extracted from satellite images and they were

Table 8.1 Correlation matrix for different damage categories, as obtained from satellite images and field verification

Damage level	Categories as extracted from satellite images				
	Category	High	Moderate	Low	Total
Categories as verified in the field survey	High	21	2	0	24
	Moderate	2	25	2	29
	Low	1	3	18	22
	Total	24	30	20	74

also verified in the field. Then the "Correlation matrix" method according to Congalton (1991) was applied for the 74 localities. Table 8.1 shows the correlation between the two data sources with regard to the damaged zones. For example, the data obtained from satellite images and from field verification coincide in identifying 21 localities with high-level damages. However, two localities that were classified as high-level on the basis of satellite images were found to be at the moderate-level in the field survey. There is also one locality that was considered high-level from satellite images, but in the field was found to be low-level. All data were treated according to this procedure of comparison.

As indicated in Table 8.1, if we consider all coincided values (in the yellow diagonal column) and compare them with the total 74 variables (the blue frame), the correlation percentage is 86 %. This shows a creditable coincidence between the two data sources. The resulted error (i.e. the remaining 14 %) can be attributed to the time that elapsed between the date when the event occurred and the date when the satellite images were retrieved, as well as to the timing of the field verification, which was also after the satellite images were taken.

8.3 Influencing Factors in Floods and Torrents

There are several factors that act in the process of floods and torrents and thus govern the extent of resulting damages. These factors differ between regions according to the physical and anthropogenic systems that exist there. However, while some factors motivate the occurrence of floods and torrents, other factors do not, and may in fact act to reduce the hydrologic process of flooding. That said, the occurrence of floods and torrents is often controlled by three major parameters. These are: (1) climate, which is the source; (2) terrain surface characteristics, and (3) the human activities on this surface. Whilst the first two parameters are natural and largely beyond human control, the third one relates to human interference at various levels. Naturally-controlled flood risk maps are produced by integrating the natural factors, regardless of the anthropogenic ones.

In order to integrate these factors in a modeling approach to produce a naturally-controlled floods and torrents risk map, they must first be accurately determined, and as mentioned previously, these factors differ regionally. However, there are several factors that must be accounted for in a reliable modeling approach (Al-Saud 2010a). These are:

1. Anthropogenic controls should be eliminated in this model, so that only the physical factors that influence floods and torrents are included. In this case, the effect of human interference can be evaluated, and this in turn helps in decision making with regard to controls to reduce the impact of floods and torrents.
2. Rainfall should be considered as a constant control, and natural elements of the terrain surface should be investigated apart from rainfall. As shown in this study, the rainfall factor is considered constant due to the overlapping of the geographic distribution of rainfall in 2009 and 2011 which resulted in it covering almost the entire area of study.
3. A statistical coincidence procedure between the geographic distribution of damaged localities and the existent factors in the study area should be applied in order to induce the influencing factors and the magnitude of their influence. This can be undertaken by using GIS. For example, the existence of a large number of damaged localities in narrow-section valleys indicates that this factor (valley narrowness) is an influencing factor in the occurrence of floods and torrents. Therefore, it is anticipated that narrow-section valleys will be localities for floods in the event of torrential rain, and this can be applied to all regions with a similar factor.

Normally, in studying the risk of floods and torrents, geomorphologic and hydrologic parameters are primarily diagnosed and then all the factors indicated by those parameters are investigated. As discussed in the section on basins, the results of this will indicate susceptibility to floods and torrents. However, this may be inaccurate, since different localities in the same basin may have diverse characteristics. Therefore, it would be more reliable to treat the influencing factors on the basis of geographic distribution, even if they extend to different basins in the area of study.

Proper integration of factors will give precise results if these factors are accurately modeled. Any errors that arise may be attributed to:

1. Integration of non-influential (or negligible) factors in the modeling procedures to produce the flood risk map.
2. Erroneous classification of the influencing factors, such as the relation of drainage density with respect to water flow on gentle or steeply sloping terrain.
3. Inaccuracy in the systematic data integration in the GIS system, and in the ranking of factor effectiveness.
4. Inaccurate processing of satellite images, notably with respect to spatial resolution.

In order to avoid these erroneous results, and since the study area has already witnessed floods and torrents and the damaged localities have already been determined, it is essential to analyze the data and information that collected, and thus identify the "coincidence"between the damaged localities and the existing factors. This will help in identifying the effectiveness of the influencing factors in the process of flooding.

The following steps can be implemented in applying this coincidence approach:

1. Using the map of damaged localities in Jeddah with its three classes (Fig. 8.3) as an indicative map. The reliability of this map, which was produced from high-resolution analysis of satellite images that were acquired after the floods and torrents of November 2009 and January 2011, was verified in the field.
2. Determining the geographic distribution of the influencing factors. This includes even the factors that are distributed in various places and even those within the same basin, and not dealing with each basin separately. For example, the geometric characteristics of basins will not be included in the coincidence procedure, because it treats the entire geometric shape of the basin and not the geographic distribution of the influencing factors within it; although this characteristic (i.e. basin geometry) was used to assess the general setting of the basin with respect to floods and torrents (Chap. 6). In addition, the factors to be integrated should be classified into different *Weights* (i.e. levels of influence). For example, if a damaged locality coincides with a depression, this is evidence that there is one category (i.e. depressions) to be considered, but if this coincidence is with drainage density, which has three classes (high, moderate and low), then three categories must be considered (Fig. 8.4).
3. Applying systematic digital coincidence in the GIS system for the three damage levels and the influencing factors (Fig. 8.3). Therefore, the percentage

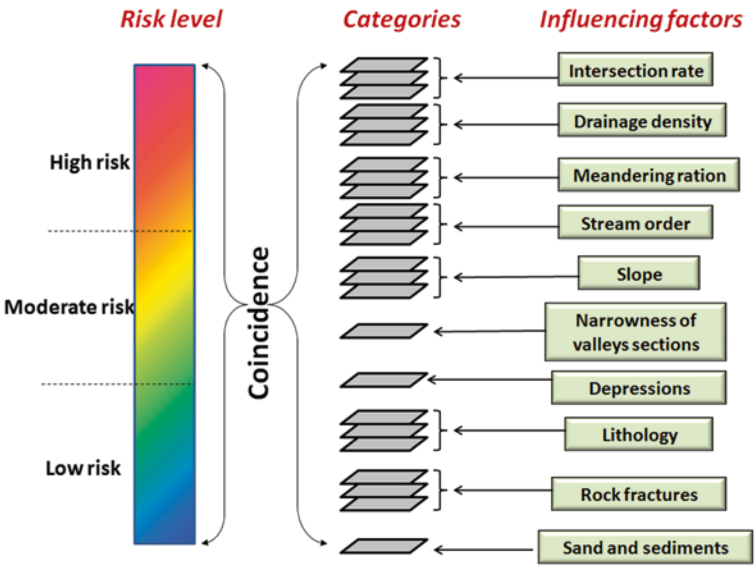

Fig. 8.4 Estimated weights of the factors influencing floods and torrents in Jeddah area

of coincidence will be induced between different categories and variables (Table 8.2). In this stage of the study, the applied modeling approach was the same as the one used previously by the author (Al-Saud 2010a).

The above-mentioned coincidence approach was accomplished in the GIS system, and more accurately in Arc-GIS 9.3, by overlapping different thematic maps, each of which represents an influencing factor according to the proposed model, as applied by the author in a previous study (Al-Saud 2010a). This was obtained by the overlapping of the damaged localities and their geographic distribution with respect to different influencing factors. Therefore, the percentages of coincidence were precisely calculated (Table 8.2), and they were also indicative of the degree of effectiveness (i.e. weights) for each factor in the process of floods and torrents. These weights were used in the systematic production (in GIS) of the flood risk map, where each factor was given its own weight of influence.

The overlapping of different factors, which were digitally formatted, was applied to induce the importance of the influencing factors in the hydrologic process. However, there is an obvious diversity in the degree of influence between the manipulated factors, which are actually existent and act in the mechanism of floods and torrents. This is certainly the case with Jeddah and its surroundings. Consequently, a number of diverse weights resulted for each factor, as shown in Fig. 8.5. These weights were manipulated digitally for each factor in the GIS system.

It is clear from the application of the coincidence approach that sands and sediments, depressions, narrow valley sections and intersected tributaries were the most influential factors, with percentages of 47.74 %, 39.22 %, 37.16 % and 23.65 % respectively. However, these percentages depend mainly on the frequency of coincidence between damaged localities and physical characteristics, which were systematically represented by the influencing factors. This means that floods and torrents may occur in localities other than those that witnessed the flood events in 2009 and 2011, but with less probability, unless an anthropogenic factor exists.

8.4 Mapping Floods and Torrents Risk

Usually, an indicative map is obtained for areas at risk of natural hazard by determining the fundamental factors that act in natural processes, which are described here as “influencing factors”. In the present study this was done over different stages of the investigation into floods and torrents, based on the damages incurred in the area of Jeddah in November 2009 and January 2011. It was clear from this that influencing factors have different levels of effectiveness, i.e. weights, as discussed in the previous section. This makes it necessary to rank each factor while modeling them to produce a flood risk map.

Mathematical modeling can be obtained by manipulating the influencing factors, which are represented together digitally in the GIS system, after converting each factor to its percentage of effectiveness, i.e. weight (Table 8.2 and Fig. 8.5). This

Table 8.2 Coincidence between the influencing factors and damaged localities from floods and torrents in Jeddah area in 2009 and 2011. (According to the map of damaged localities from floods and torrents in Jeddah area (in Fig. 4.4))

Influencing factor	Category	Damage level	Coincided area (km^2)	Coincidence percentage (%)	Average percentage of effectiveness	
Intersection rate (Table 12)	Dense (2 nodes/km^2)	High	13.54	63.90	21.71	23.65
		Moderate	6.50	28.74		
		Low	1.67	7.33		
	Moderately dense (1.5–2 nodes/km^2)	High	11.41	50.31	22.68	
		Moderate	8.24	36.33		
		Low	3.03	13.36		
	Slightly dense (1.5 nodes/km^2)	High	10.10	38.04	26.55	
		Moderate	7.24	27.27		
		Low	9.21	34.69		
Drainage density (Table 10)	Dense (2 km/km^2)	High	6.08	60.07	10.12	11.53
		Moderate	2.15	21.24		
		Low	1.90	18.77		
	Moderately dense (1–2 km/km^2)	High	6.39	53.92	11.85	
		Moderate	3.14	26.49		
		Low	2.32	19.57		
	Slightly dense (1 km/km^2)	High	5.93	46.95	12.63	
		Moderate	2.94	23.27		
		Low	3.76	29.77		
Meandering ration (Table 12)	High (1.2)	High	2.60	67.18	3.87	2.85
		Moderate	0.84	21.70		
		Low	0.43	11.11		
	Moderate (1.1–1.2)	High	1.23	50.82	2.42	
		Moderate	0.74	30.57		
		Low	0.45	18.59		
	Low (<1.1)	High	0.89	39.20	2.27	
		Moderate	0.65	28.63		
		Low	0.73	32.16		
Stream order (Table 11)	High (2.5)	High	7.34	31.96	22.96	19.63
		Moderate	6.52	28.39		
		Low	8.10	35.27		
	Moderate (1.5–2.5)	High	3.27	23.61	13.85	
		Moderate	3.54	25.55		
		Low	7.04	50.83		
	Low (1.5)	High	11.08	50.18	22.08	
		Moderate	6.11	27.67		
		Low	4.89	22.14		

Table 8.2 (continued)

Influencing factor	Category	Damage level	Coincided area (km^2)	Coincidence percentage (%)	Average percentage of effectiveness	
Slope (Table 7)	High (20)	High	5.11	44.86	11.39	11.33
		Moderate	2.47	21.68		
		Low	3.81	33.45		
	Moderate (10–20)	High	9.78	49.87	19.61	
		Moderate	4.55	23.20		
		Low	5.28	26.92		
	Low (10)	High	1.56	51.82	3.01	
		Moderate	0.88	29.23		
		Low	0.57	18.93		
Narrowness of valley section	Locality on narrow cross-section	High	23.56	63.40	37.16	
		Moderate	8.43	22.68		
		Low	5.17	13.91		
Depressions	Lands below that terrain surface	High	24.39	62.18	39.22	
		Moderate	9.49	24.19		
		Low	5.34	13.61		
Lithology	High infiltration rate (30%)	High	0.47	9.65	4.87	7.51
		Moderate	1.47	30.18		
		Low	2.93	60.16		
	Moderate infiltration rate (10–30%)	High	5.23	42.76	12.23	
		Moderate	4.34	35.48		
		Low	2.73	22.32		
	Low infiltration rate (10%)	High	2.15	39.45	5.45	
		Moderate	1.80	33.02		
		Low	1.50	21.52		
Rock fractures	Fracture density (>10 fractures/25 km^2)	High	5.27	40.63	12.97	9.47
		Moderate	4.53	34.92		
		Low	3.17	24.44		
	Fracture density (5–10 fractures/25 km^2)	High	1.48	26.24	5.64	
		Moderate	1.07	18.97		
		Low	3.09	54.78		
	Fracture density (5 fractures/25 km^2)	High	6.25	63.77	9.80	
		Moderate	2.34	23.87		
		Low	1.21	12.34		
Sand and sediments	Area of the existing sediments	High	31.02	64.97		47.74
		Moderate	9.27	19.41		
		Low	7.45	15.60		

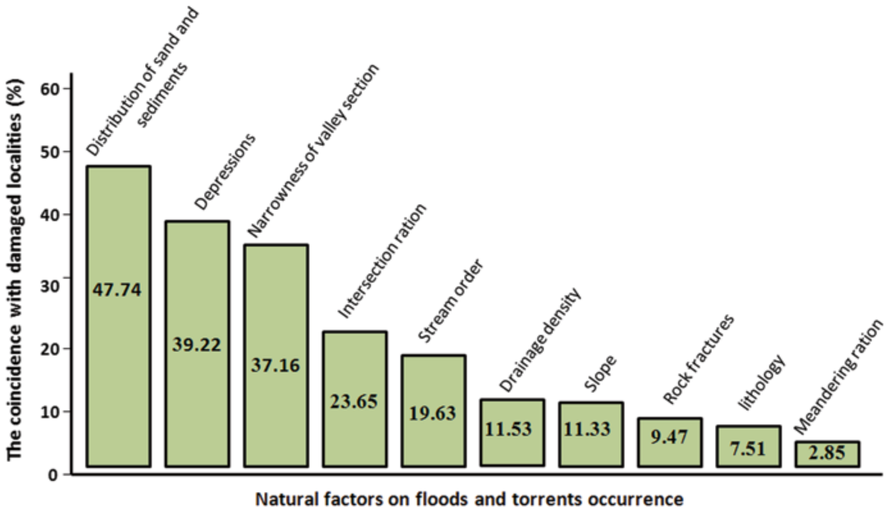

Fig. 8.5 Weights of factors effectiveness in floods and torrents in Jeddah area

follows the same systematic approach adopted by Al-Saud (2010b). Therefore, each factor will be represented by its weight of influence which was induced from the existed damage in Jeddah and the surrounding area.

For example, valley intersections have a 23.65 % weight (i.e. degree of coincidence), while rock fractures have a 7.51 % weight. This means that the *factor influence* acts as a separate component, apart from the other factors. Therefore, to calculate the effect of each factor with respect to the total effectiveness, the sum of effectiveness for all these factors must first be calculated and then each will be divided on the resulting sum in order to calculate the effect of a specific factor on the whole process. The following equation represents the mathematical components to calculate the sum of effectiveness for factors.

Sum of effectiveness for all factors = Meandering ration (%) + Drainage density/3 (%) + Slope/3 (%) + Intersection rate (%) + Narrowness of valley section (%) + Depressions (%) + Lithology/3 (%) + rock fractures/3 (%) + Sand and sediments (%) + Stream order/3 (%)

$$T_f = f_1 + f_2/3 + f_3/3 + f_4 + f_5 + f_6 + f_7/3 + f_8/3 + f_9/3 + f_{10}/3$$

Where T_f *is* the sum of effectiveness for factors, f_1 is the weight of factor number one, and so on.

According to the descriptive values of the influencing factors in Table 8.3 and Fig. 8.5, the sum of effectiveness for all factors will be:

$$23.65 + 11.5 + 2.85 + 19.63 + 11.33 + 37.16 + 39.22 + 7.51 + 9.47 + 47.74 = 210.09$$

Table 8.3 Percentages of coincidence and the real weights for the influencing factors in floods and torrents

Real weight (%)	Coincidence (%)	Influencing factors
22.72	47.74	Sand and sediments distribution
18.67	39.22	Depressions
17.68	37.16	Narrowness of valley section
11.26	23.65	Intersection rate
9,34	19.63	Stream order
5.49	11.53	Drainage density
5.39	11.33	Slope
4.50	9.47	Rock fractures
1.70	7.51	Lithology
1.36	2.85	Meandering ration

In the case of factors which are represented by three categories, the average value will be calculated. In addition, the coincidence approach will be applied either to the maximum or minimum values among the factors with three categories. Hence, the trend of influence should be primarily determined. In other words, factors with three categories should be attributed whether their maximum or minimum influence acts in the occurrence of floods and torrents, as indicated by damaged localities. For example, if the middle category (of a factor with three categories) is coincided with a damaged locality, it will not be an indication of influence.

Therefore, the percentage of influence of any of the ten factors in the occurrence of floods and torrents can be calculated according to the following equation:

Percentage of factor influence in floods and torrents occurrence = Coincidence ratio of effectiveness for all factors.

$$I_r = C_r / T_r \times 100$$

Where I_r is the percentage of influence of a specific factor, and C_r is the percentage coincidence.

By applying the above equation and calculating the percentage of influence for each factor to the whole percentages of all factors (i.e. 210.09), the real weights can be calculated (Fig. 8.6).

The map digitally produced from mathematical modeling in the GIS system reveals the natural risk of floods and torrents in Jeddah city and the surrounding area (Fig. 8.6), regardless of any human interference. This map, which has three risk levels, shows that the total area of the risk zones is about 264.2 km^2, which is equivalent to 13.56 % of the study area (i.e. 1947 km^2). Among these risk zones, about 109.4 km^2 are characterized by high susceptibility to floods and torrents (i.e. the first risk-level). This means that about 5.61 % of the whole studied region is at high natural risk of floods and torrents.

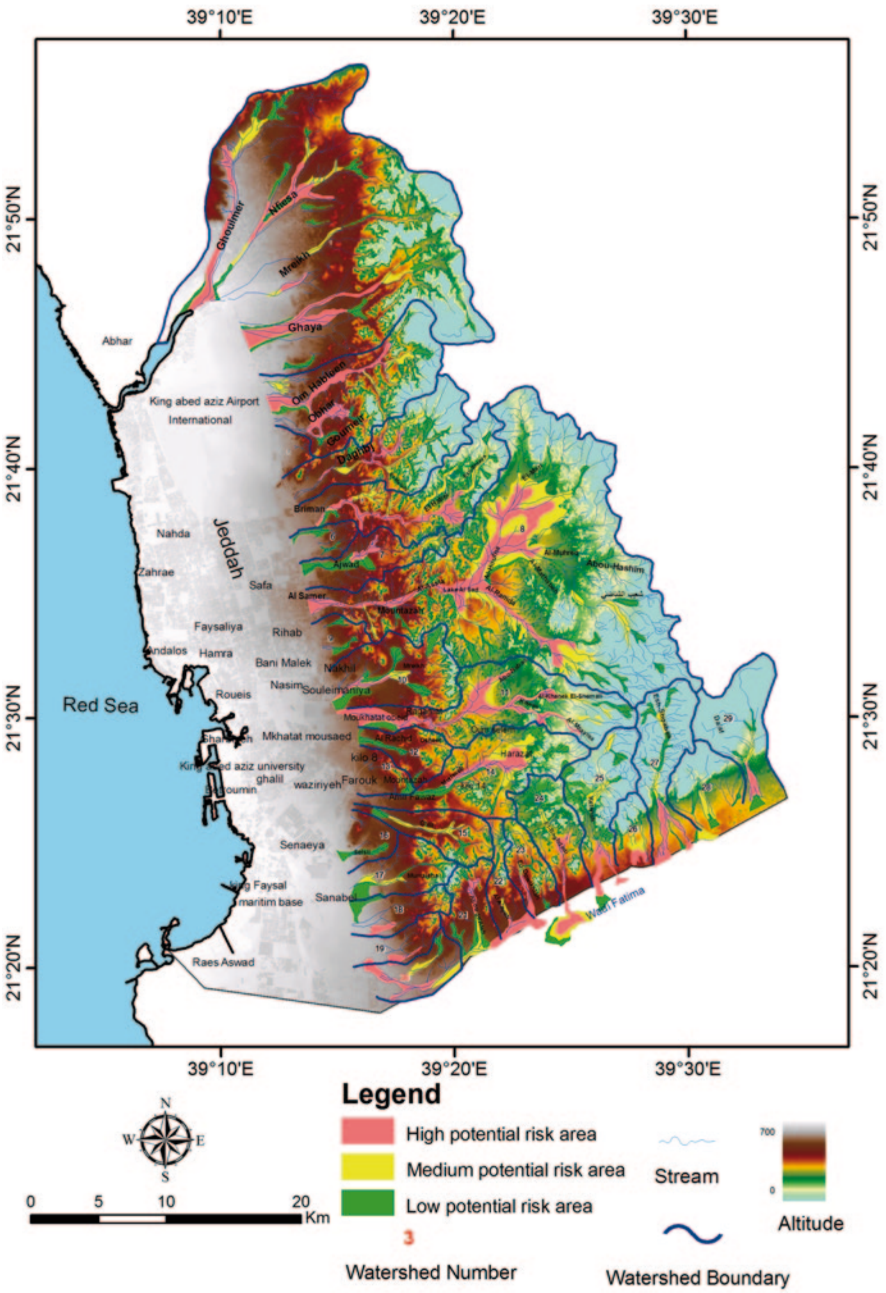

Fig. 8.6 Natural floods and torrents risk map (without human interference) in Jeddah City and the surroundings

This map, which is not indicative of any anthropogenic impact and totally integrates with physical characteristics, shows that the geographic distribution of flood water is mostly related to terrain components. One of the remarkable features is the elongated shape of accumulated flood water, which is governed solely by valley alignments. The difference in the geography of flood risk zones determined in Fig. 4.4 and Fig. 8.6 shows the degree of impact is governed solely by valley human interference.

It is also important to correlate the geographic distribution and aspect of flood water with the degree of damage. Therefore, any flood water which is not harmful to humans and the environment will not be considered as risk, but simply encountered as a natural phenomenon.

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Chapter 9
Localities Damaged by Floods and Torrents

Abstract The identification of localities which have been subjected to damages by floods and torrents is essential to understand the behavior of water flow, as well as to deduce how various terrain surfaces respond to running and accumulated water. This involves locating the geographic distribution of damaged zones and assessing the impact of damage. Comparing these localities in terms of their physical and anthropogenic characteristics will help in predicting which areas are at flood risk. Such an approach has been applied in this study.

This chapter describes the characteristics of the localities that have witnessed floods and torrents in the Jeddah area, notably in the events of 2009 and 2011; these are called "hotspots". Thus it forms the groundwork for the proposal of flood controls in each locality, which will help to mitigate the recurrence of such events, notably in those areas that were identified as vulnerable to floods and torrents by satellite images and field survey.

The resulting risk map (Fig. 8.5) integrates several influencing factors in the occurrence of floods and torrents apart from the factor of human interference. This in turn reflects the impact of anthropogenic factors in the disastrous events that have occurred in the area of concern in the last few years. The author has carried out a series of studies on these events (Al Saud 2009; 2010a), in the process of which the extracted information from satellite images was compared with the data plotted on the map by mathematical modeling in the GIS system. Empirical coincidence was found between these two data sources. The map produced from the modeling of influencing factors was subsequently modified.

In this part of the study, localities damaged by floods and torrents in the years 2009 and 2011 were examined and assessed in terms of level of risk. This enables the proposal of flood controls to reduce or mitigate floods and torrents. To this end, five flood risk categories were classified and plotted as shown in Fig. 7.1, ranging from 1st risk category (i.e. most catastrophic impact) to 5th risk category, which represents localities saturated by water, but incurring no considerable damage.

According to data and information obtained with regard to rainfall intensity and the resulting damages, as well as to the geographic distribution of damaged localities, it is predicted that a catastrophic event will occur if torrential rainfall reaches

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120 mm within a couple of hours. This would ensue if the current situation remains and no water flow controls were implemented. In the face of changing climatic conditions, this issue needs to be urgently considered.

The resultant damages in the study area are in direct proportion to the risk levels. This means, for example, the 2nd risk category may be extended to the 1st risk category in the case of excessive rainfall, and the 3rd risk category may be extended to the 2nd one and so on. In addition, it must be considered that while a risk can originate from one locality, its impact may extend to another locality. For example, some risks have originated from upstream localities, but the water has run along valleys and accumulated in remote downstream localities. This is well pronounced in areas where human settlements exist, as a result of the unfavorable impact between running water and building construction. Therefore, the following parameters were treated in this study:

1. *Anthropogenic impact*
   This is represented by the existence of settlements and human activities, which affects the degree of flood water impact, as indicated by the risk map (Fig. 4.4). However, while there were vast areas that were subject to severe flooding, they were not assigned to the 1st risk category, but mostly to the 2nd or 3rd risk categories. This is due to the absence of urban areas, which means that less damage was incurred. Such was the case in many localities affected by the flood of November 2009, where large areas were covered by water but there were no urban settlements; consequently these areas were not even mentioned in the media.
2. *Water seeps*
   Many localities were characterized by water seeps and were described as low-risk areas (i.e. 4th or 5th risk category). However, the source of water in these localities was not considered. For example, water derived from Wadi Mriekh and Wadi Kawes entered urban areas along roads and natural routes, and thus reached localities that did not witness any rainfall.
3. *Existence of obstacles*
   This property is considered along watercourses and their influence in creating floods and torrents. That is, it represents cases where running water has stopped not because of physical controls, but due to obstacles created by urban construction such as roads, dams etc. Such obstacles limit the flow of water and sediments. Therefore, these localities were considered at risk in the light of the expectation that if these constructions were destroyed, then severe damage may result.

In this study "*hotspots*" were determined only for the major risk levels (i.e. 1st, 2nd and 3rd risk categories), and they were plotted on a unique map (Fig. 9.1). In the study area, there are six localities of the 1st risk category, and seven localities of the 2nd risk category. Some examples of the 3rd risk category were recognized. The 4th and 5th risk categories, of which there are a great many in the area of study, were not included on these maps since their impact is minimal and there must be heavy torrential rain for these risk levels to occur. Nevertheless, the localities of such low risk levels can be recognized on the flood risk map (Fig. 4.4).

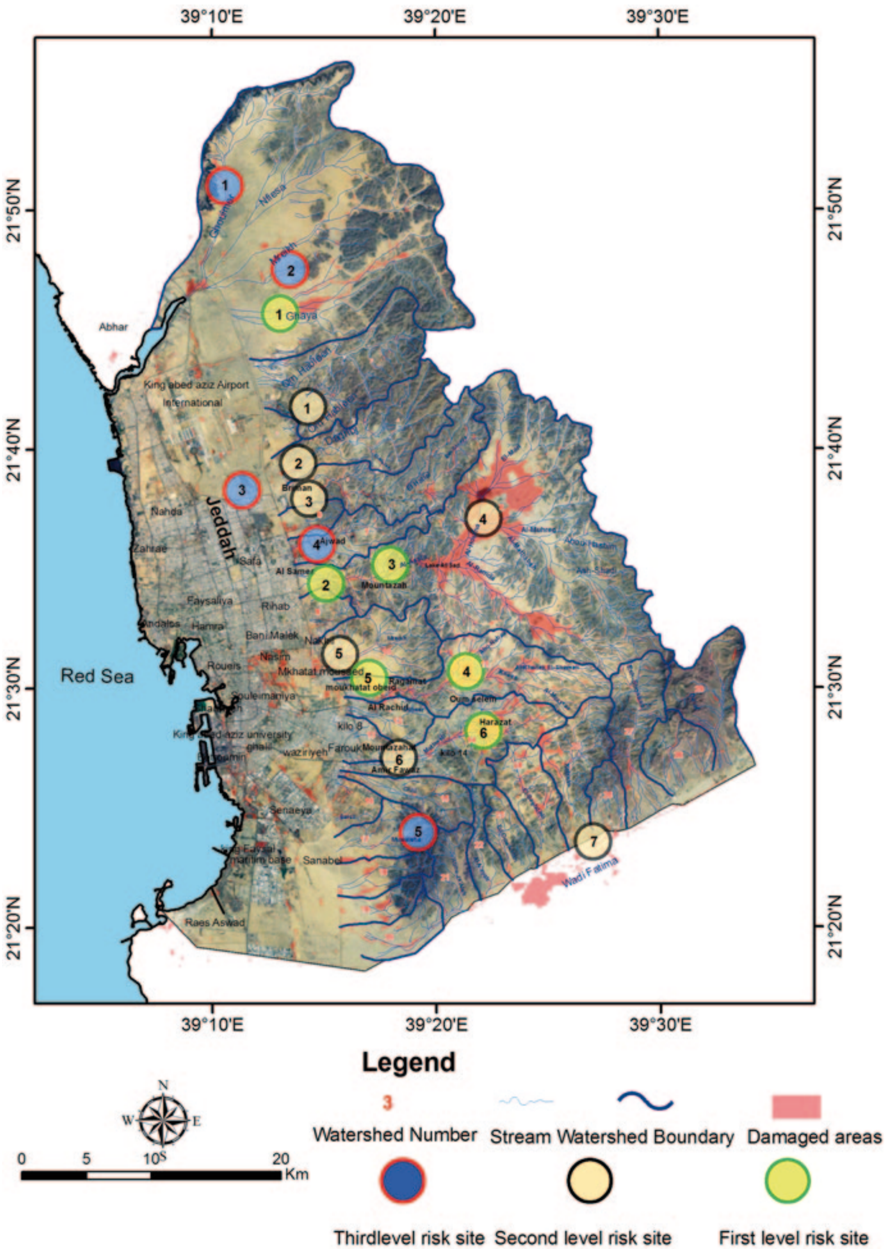

Fig. 9.1 Localities under three floods and torrents risk levels (1st, 2nd and 3rd) in Jeddah area

9.1 First Risk Category Localities

This risk category mostly represents intensive water coverage where many depressions were filled with water, accompanied by rapid and high energy flow, notably along valley courses. The running water also carried large amounts of sediments and debris. In the Jeddah area, the damages of this risk category are common in the localities of: (1) wide valley courses, (2) impact sites between running water and urban settlements, and (3) valley cross-sections with narrow conduits for the transmit of water.

The impact of this risk category includes, in addition to natural and urban aspects, impact on humans at various levels (e.g. deaths, casualties etc). There are six localities that are characterized by the impact of the 1st risk category (Table 9.1 and Fig. 9.1). The position of these localities is plotted on the maps of figs. 9.2, 9.3, 9.4, 9.5, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, 9.12, 9.13, (Ordered from north to south). In this study, there are two maps for each locality. The first map shows the locality from the DEM aspect, while the second one shows the geographic domain of the risk zone.

Table 9.1 Localities of the 1st risk Category

Locality No	Name of the area	Coordinates[a]	Damage description
1	Al-Hamdanieh-Al-Falah (Wadi Ghaya)	21° 46’ 00” & 39° 13’ 00”	There is huge amount of water with heavy bed load of sediments and mud that derived from different valleys and discharged at the urban zone of Al-Hamdanieh-Al-Falah. This water load and sediments stopped at the existing road, which extends in opposite direction to the valley course. This load may pass over the road and then invade the urban areas
			Fig. 9.2 & 9.3
2	Es-Samer Dam	21° 34’ 30 & 39° 15’ 15”	Restriction of large amounts of water into a narrow cross-section of Wadi El Assla. The rise of water level behind the dam is dangerous in the case the dam is damaged or even cracking, notably as there are urban areas behind the dam
			Fig. 9.4 & 9.5
3	Precautionary Dam (Es-Sad El-Ehterazzi) area	21° 35’ 00 & 39° 18’ 00”	There is a joining between a number of valleys which discharge water towards the Precautionary Dam. However, the increase in the load of discharged water may result in collapsing of the dam, and will impact the downstream urban zone along Wadi EL Assla. This locality is connected with Locality No. 2 (Es-Samer Dam)
			Fig. 9.6 & 9.7
4	Wadi Abou Nabaa area	21° 30’ 30 & 39° 21’ 00”	There is a joining between the tributaries of Wadi Al-Khaneq El-Shamali, Wadi El-Mzyraah, and both discharge in a narrow section of Wadi Abou Nabaa, and then between hilly rock masses, which made the running water and sediments injected between these hilly rocks towards the downstream area.
			Fig. 9.8 & 9.9
5	Al-Raghama-Kwaiza area	21° 30’ 00 & 39° 17’ 00”	The restriction of Wadi Kawes in a narrow and meandered valley course, resulted injecting the running water and sediments with high energy towards urban zones, where the impact between water and human settlements occurred in areas of Kwaiza, and El-Masa’ad. Therefore, water heavily seeped after this impact towards urban zones along roads and reached remote localities, such as Abdull Aziz University, and further on to Al-Solaymanieh, Al-Nakheel which are located within Mriekh basin
			Fig. 9.10 & 9.11
6	Al-Harazat	21° 28’ 30 & 39° 22’ 00”	There is a joining between several tributaries from Wadi Methweb, one of them is narrow and outlets beside a low-land urban zone (i.e. Al-Harazat). This resulted water accumulation, and when water level rises, it flowed from a narrow site in the downstream
			Fig. 9.12 & 9.13

[a] Geographic coordinates of the mid-point of the locality

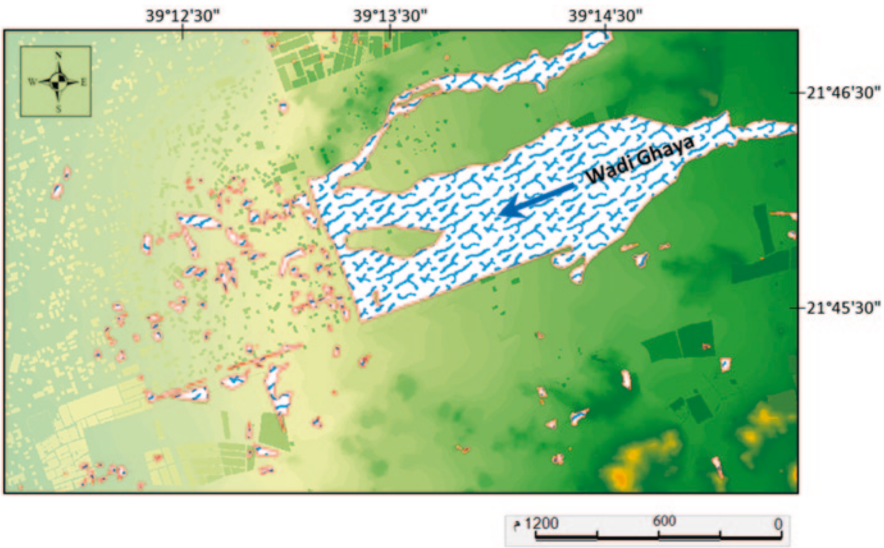

Fig. 9.2 Digital Elevation Model (DEM) for locality No. 1 of the 1st-risk Category

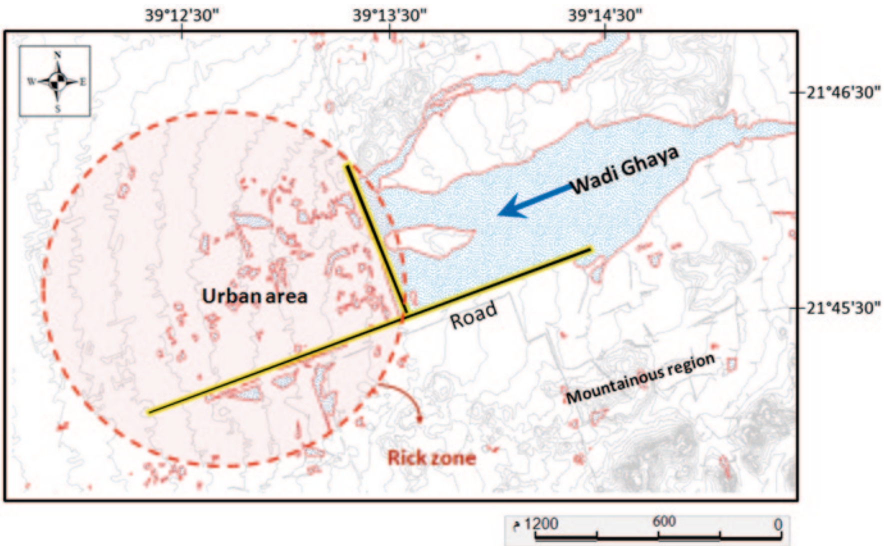

Fig. 9.3 Map showing damage distribution for locality No. 1 of the 1st-risk Category

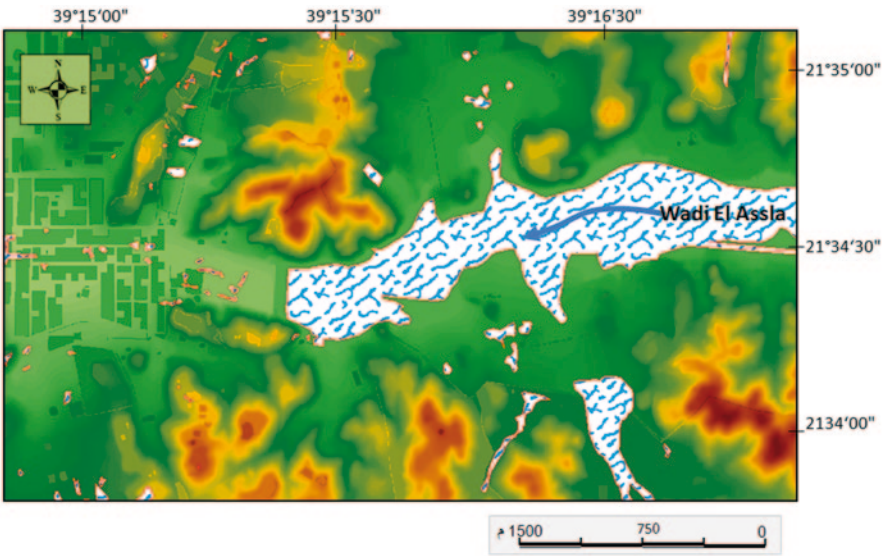

Fig. 9.4 Digital Elevation Model (DEM) for locality No. 2 of the 1st-risk Category

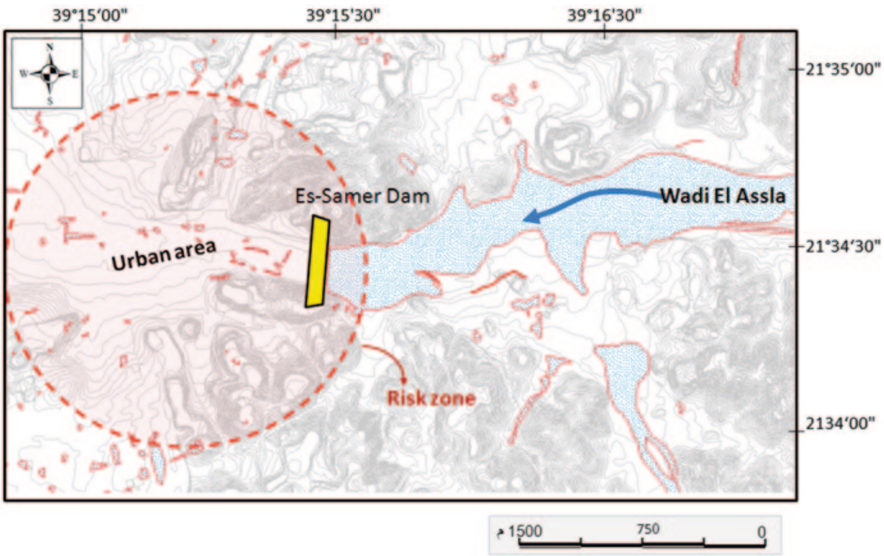

Fig. 9.5 Map showing damage distribution for locality No. 2 of the 1st-risk Category

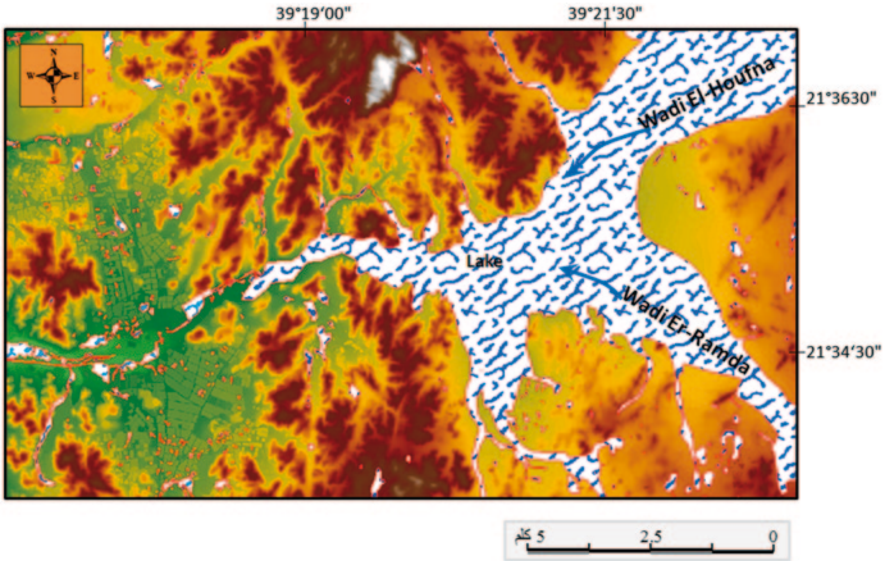

Fig. 9.6 Digital Elevation Model (DEM) for locality No. 3 of the 1st-risk Category

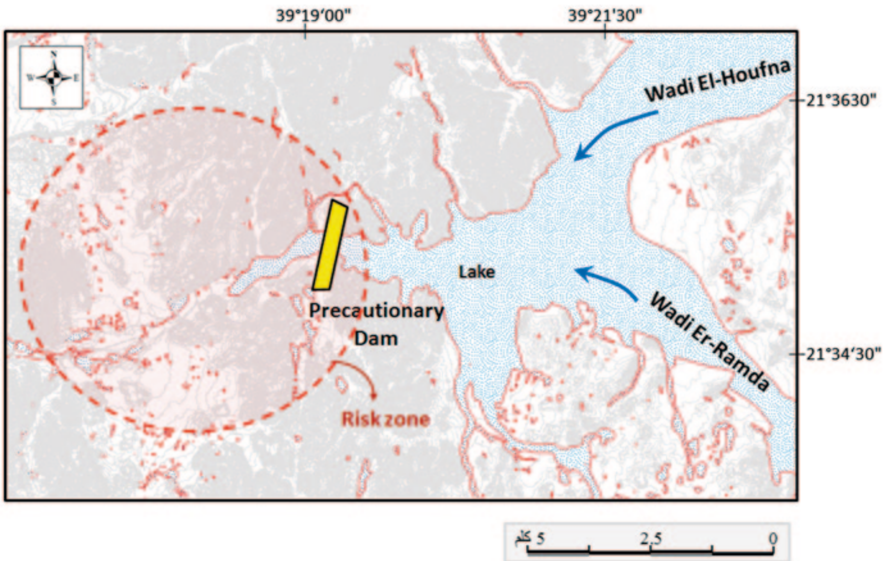

Fig. 9.7 Map showing damage distribution for locality No. 3 of the 1st-risk Category

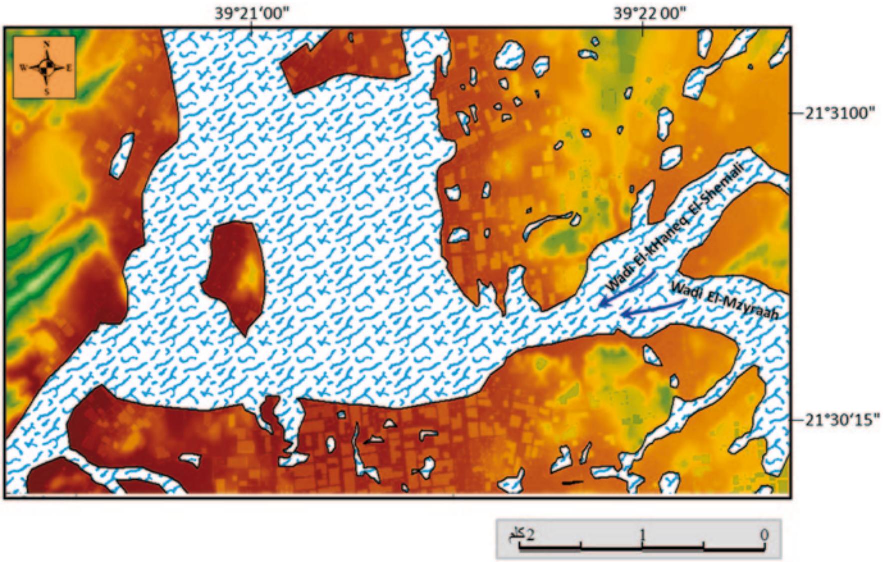

Fig. 9.8 Digital Elevation Model (DEM) for locality No. 4 of the 1st-risk Category

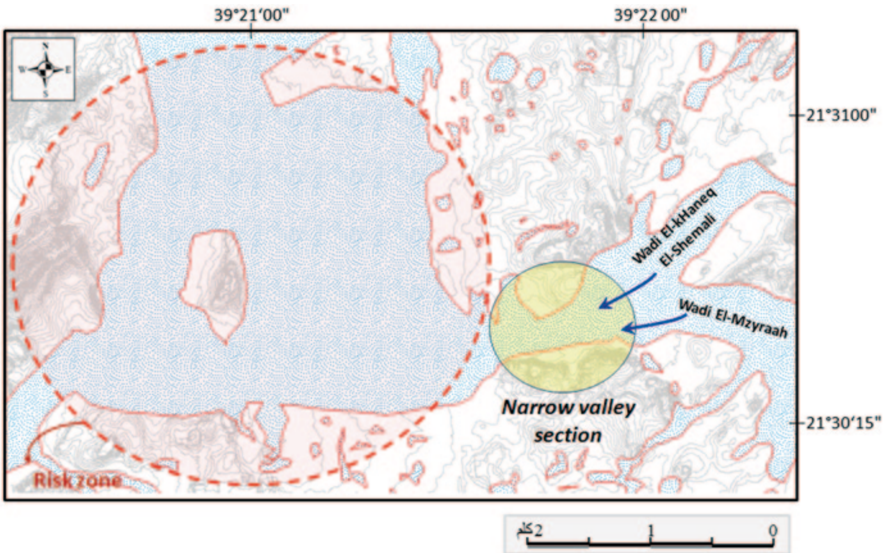

Fig. 9.9 Map showing damage distribution for locality No. 4 of the 1st-risk Category

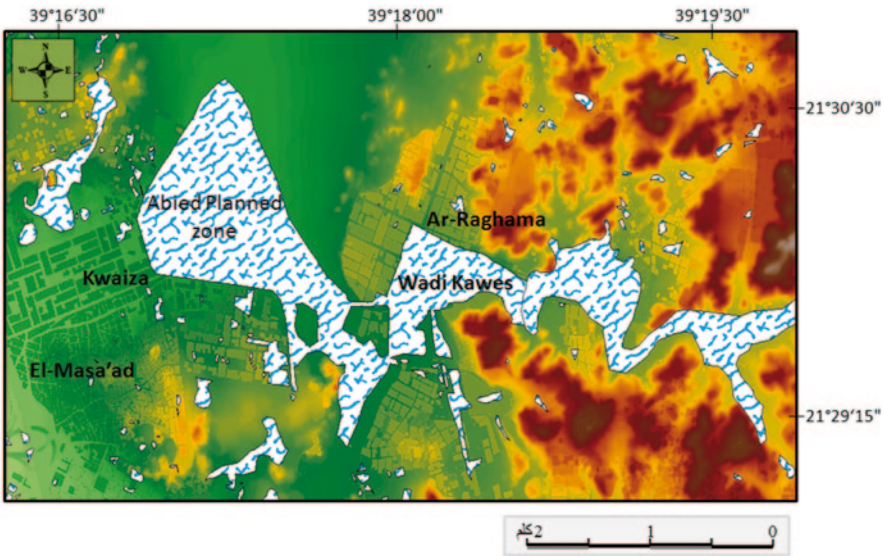

Fig. 9.10 Digital Elevation Model (DEM) for locality No. 5 of the 1st-risk Category

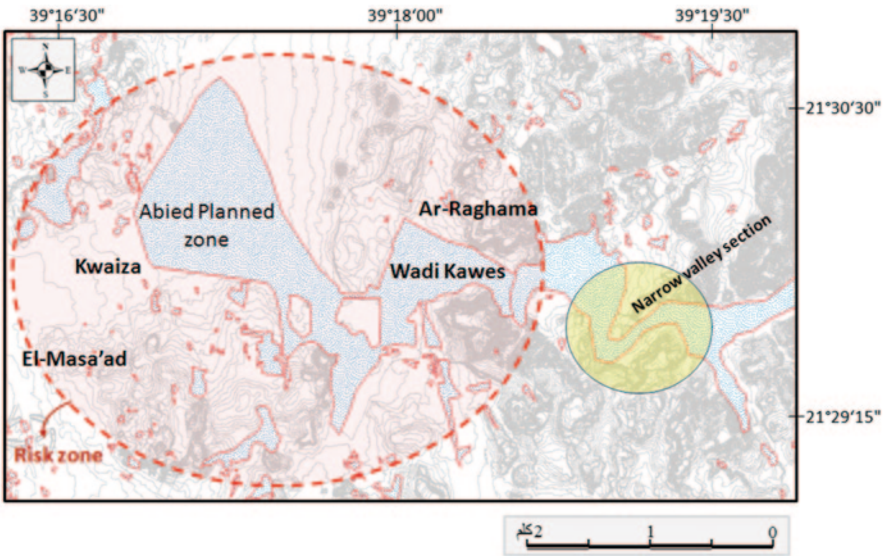

Fig. 9.11 Map showing damage distribution for locality No. 5 of the 1st-risk Category

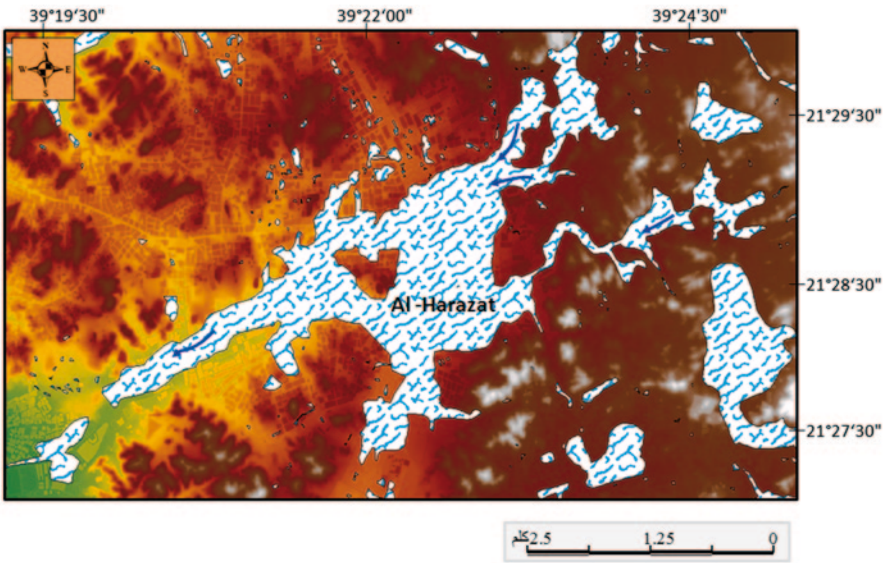

Fig. 9.12 Digital Elevation Model (DEM) for locality No. 6 of the 1st-risk Category

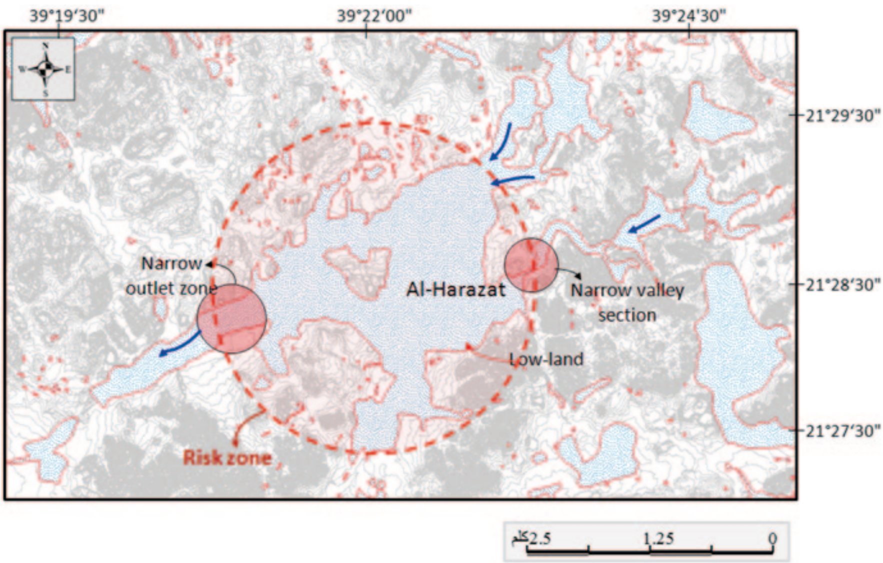

Fig. 9.13 Map showing damage distribution for locality No. 6 of the 1st-risk Category

9.2 Second Risk Category Localities

In this risk category, water fills all depressions and low-lands, where the depth may exceed 1 m in many localities, notably in deep depressions, while water overflows from shallow depressions. In addition, the water flow rate is mostly high to moderate with considerable bed loads of sediments and mud. In this risk category, drifts existed in many places; especially in localities of unconsolidated rock and soil materials. Localities close to the running water were damaged, resulting in casualties.

With regard to the localities of this category, an increase in the rainfall rate may raise it from the 2nd to the 1st risk level. This is will be pronounced since most of these localities are situated at the end-points of water flow, which means that any exceeded flow energy can increase the degree of damage and water may extend to other areas.

According to these parameters of damage classification, there are seven localities of the 2nd risk category in the area of concern. Table 9.2 and figs. 9.14, 9.15, 9.16, 9.17, 9.18, 9.19, 9.20 show these localities (ordered from north to south).

Table 9.2 Localities of the 2nd risk Category

Locality No	Name of the area	Coordinates[a]	Damage description
1	Wadi Om Hableen area	21° 41' 00'' & 39° 14' 00''	There is a joining between a number of tributaries from Wadi Om Hableen, and thus water discharges into the neighboring urban zones, where water starts to flow along roads and in some small-scale tributaries
			Fig. 9.14
2	Wadi Daghbj area	21° 39' 00'' & 39° 15' 00''	A road cuts oppositely on the course of Wadi Deghbj, thus the flow of water is oriented along the road. Hence, there is probability of water overflow on the road and it may reach the neighboring urban zones
			Fig. 9.15
3	Wadi El Hatiel area	21° 39' 00'' & 39° 14' 30''	Wadi El Hatiel course has been subjected to many excavations, which makes it instabile, and thus many drifts occurred, notably where it outlets facing to El-Ayssani planned zone. In addition, the presence of large-section storm water channel joining with a small-section channel may cause overloading of water and sediments and mud to the neighboring urban zones
			Fig. 9.16
4	Locality of the dried El-Messek Lake	21° 36' 30'' & 39° 21'45''	There is a joining between a number of tributaries derived from instable areas and loading into the depression of the dried lake (i.e. El-Messek Lake). Thus, the loads of water and sediments may overflow with high energy when they exceed, and thus resulting risk to the downstream region
			Fig. 9.17
5	Om El-Kheir area	21° 31' 21'' & 39° 16' 00''	The presence of Wadi Mriekh, with large cross-section (>500 m) facing the urban zones of Om El-Kheir and the southern part of As-Samer may result severe condition in case of any flood process
			Fig. 9.18
6	The urban zone Al-Adel	21° 26' 30'' & 45° 17' 45''	Accumulation of seeped water from Al-Harazat area along Wadi Methweb and its joining with other tributaries caused damaging impact with urban zones of Al-Adel, Al-Ameer Fawaz and the surrounding
			Fig. 9.19
7	Wadi Fatima area	21° 24' 30'' & 39° 27' 00''	There is ajoining between the tributaries of Wadi Esh-Shoabaa and Wadi Ketanah with Wadi Fatima, which are full with thick sediments, and where urban areas exist, with a special emphasis on Al-Mejah-deen area
			Fig. 9.20

[a] Geographic coordinates of the mid-point of the locality

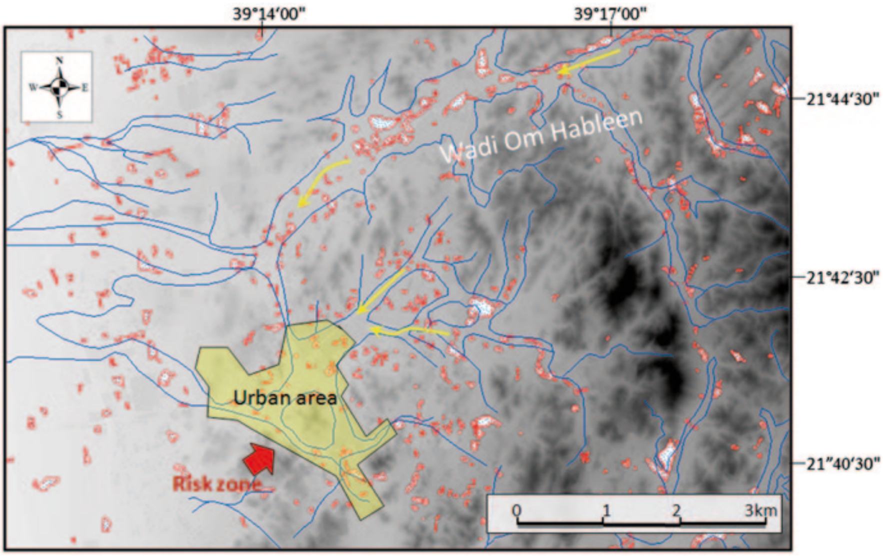

Fig. 9.14 Shaded DEM showing flood-damaged locality No. 1 of the 2nd risk Category

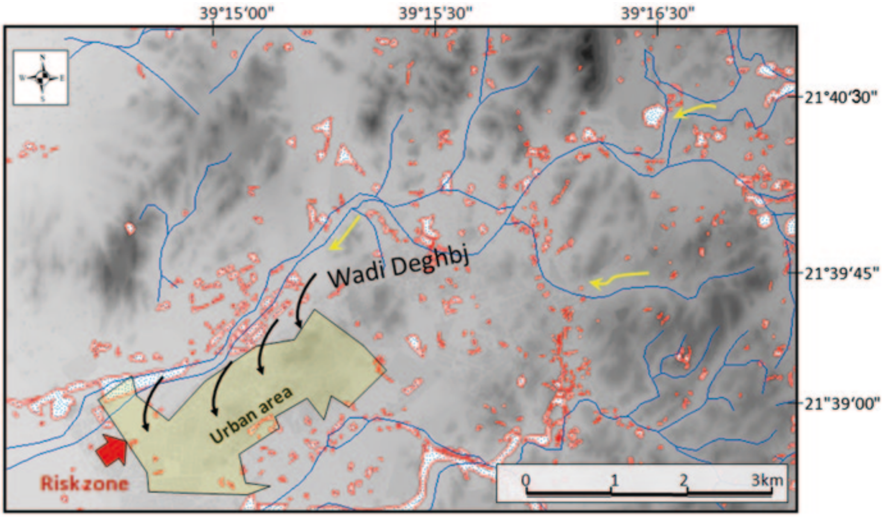

Fig. 9.15 Shaded DEM showing flood-damaged locality No. 2 of the 2nd risk Category

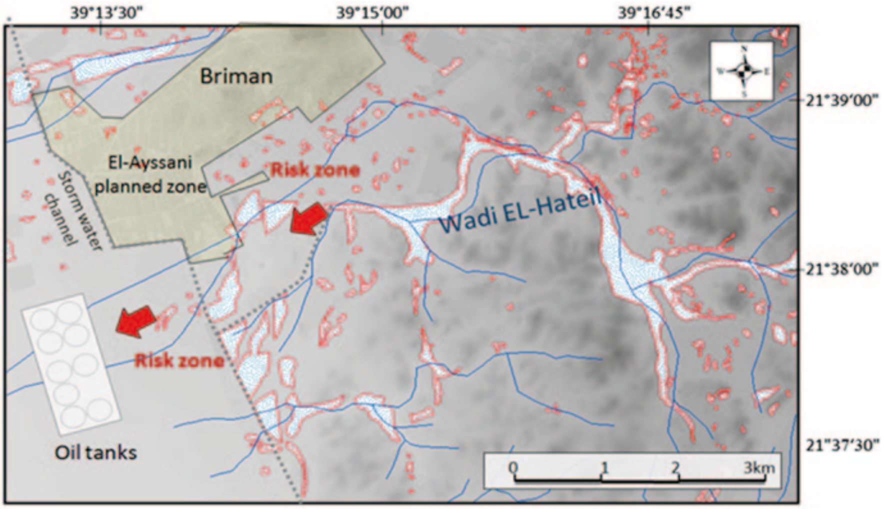

Fig. 9.16 Shaded DEM showing flood-damaged locality No. 3 of the 2nd risk Category

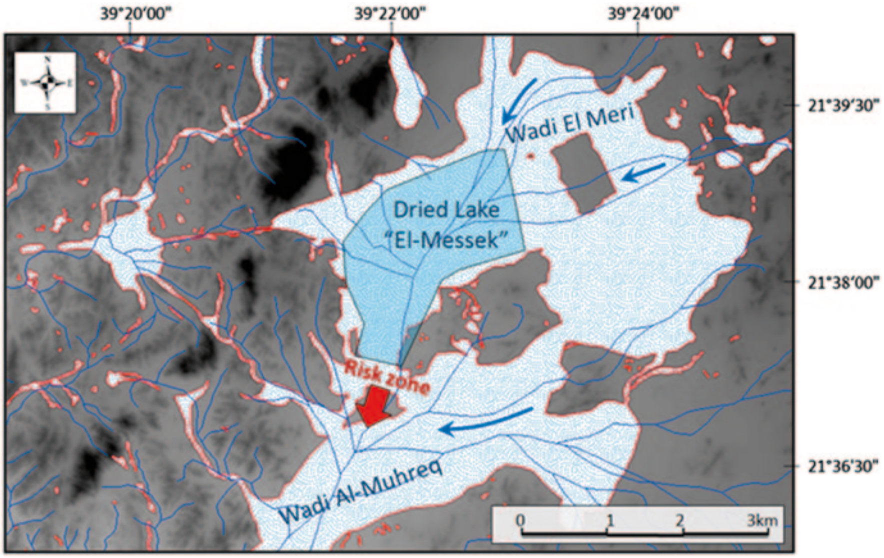

Fig. 9.17 Shaded DEM showing flood-damaged locality No. 4 of the 2nd risk Category

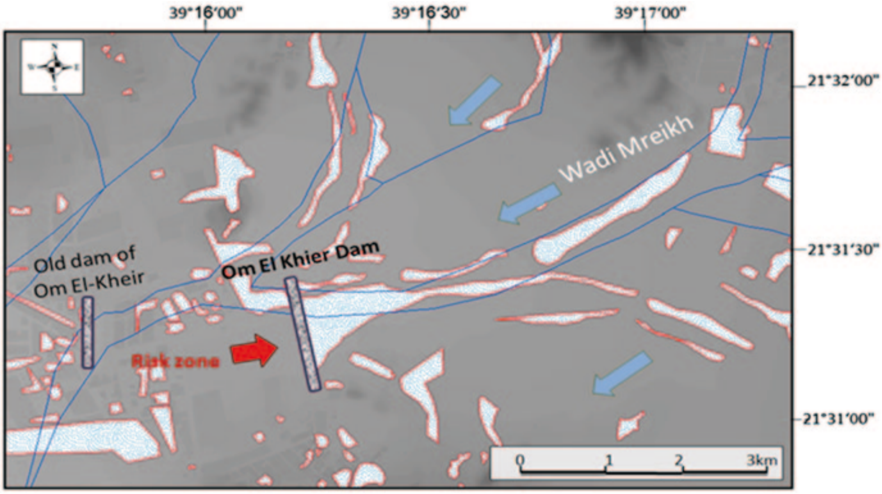

Fig. 9.18 Shaded DEM showing flood-damaged locality No. 5 of the 2nd risk Category

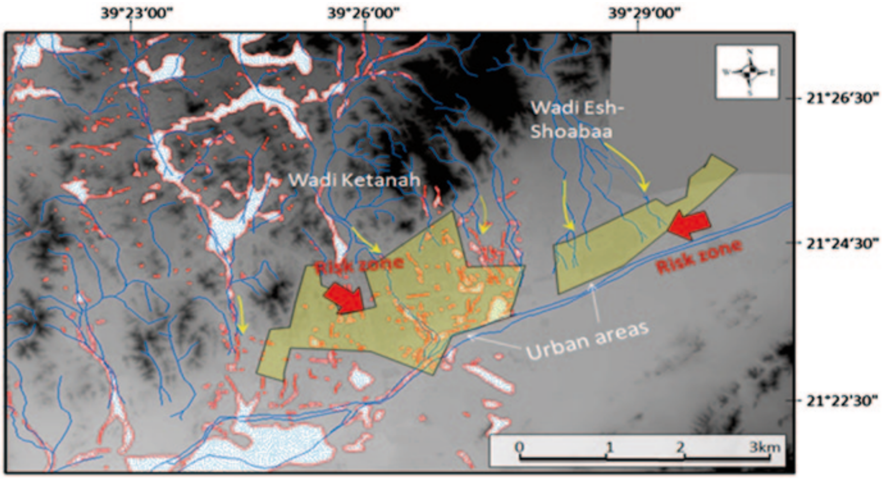

Fig. 9.19 Shaded DEM showing flood-damaged locality No. 6 of the 2nd risk Category

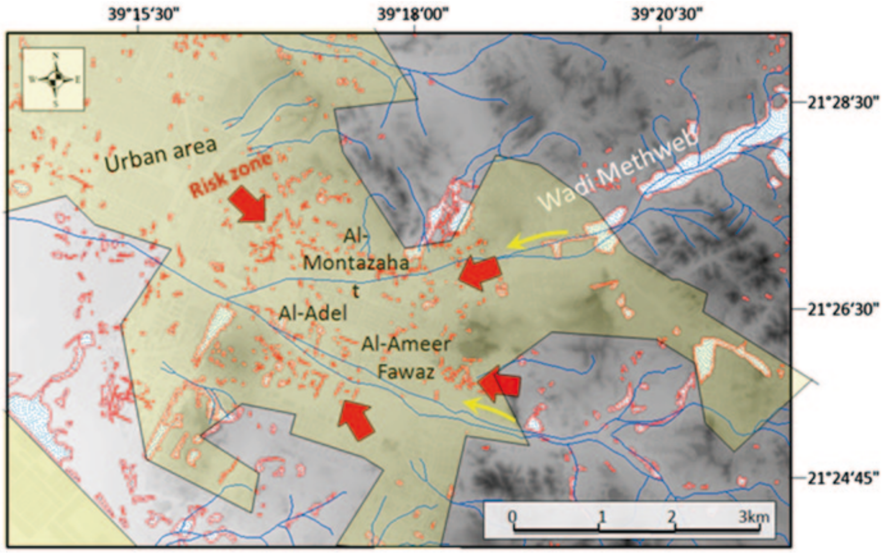

Fig. 9.20 Shaded DEM showing flood-damaged locality No. 5 of the 2nd risk Category

9.3 Third Risk Category Localities

The impact of this category occurs when moderate water flow is accompanied by local drifts. Depressions and valley courses are filled with water that may reach a depth of 1 m. In addition, water may be distributed among urban zones at various levels. The impact of this category can be harmful in some instances, although the damage is caused indirectly, resulted from drifted land masses and so on that affect human activities, causing traffic accidents etc; it also results in pollution. In the event of a rainfall rate exceeding its normal level, this category may be raised to the 2nd risk category.

Due to the great many localities of this category in the study area (Fig. 4.4), only typical examples are shown here, considering the diversity of geographic distribution, and the degree and aspects of damages; see Table 9.3 and figs. 9.21, 9.22, 9.23, 9.24, 9.25 (ordered from north to south.

Table 9.3 Example for the localities of the 3rd risk Category

Locality No	Name of the area	Coordinates[a]	Damage description
1	The surrounding of Al-Asalah and Taybah	21º 51’ 30” & 39º 10’ 15”	Water accumulation along the roads accompanied with seeps over the road and sheets of sediments which overloaded on the road sometimes
			Fig. 9.21
2	Al-Hamdanieh area	21º 47’ 15” & 39º 13’ 00”	Water in depressions and excavations in the planned zones that restricted by cement walls
			Fig. 9.22
3	Abdull Aziz International Airport area	21º 38’ 15” & 39º 11’ 00”	Dissipated water accumulations in various low-lands and depressions that are shaped according to the beneath topography. Saline groundwater intrudes from sea has a role in such accumulations, such as in Al-Maroueh area
			Fig. 9.23
4	Al-Samer-Al Manar area	21º 36’ 015 & 39º 14’ 15”	Local water flow between roads as a function of slope, and thus water runs for long distances along roads
			Fig. 9.24
5	Al-Ajaweed area	21º 24’ 00 & 39º 19’ 20”	Stored water in large amounts between mountain masses, where the infiltration is high due to the existing fractured rocks
			Fig. 9.25

[a] Geographic coordinates of the mid-point of the locality

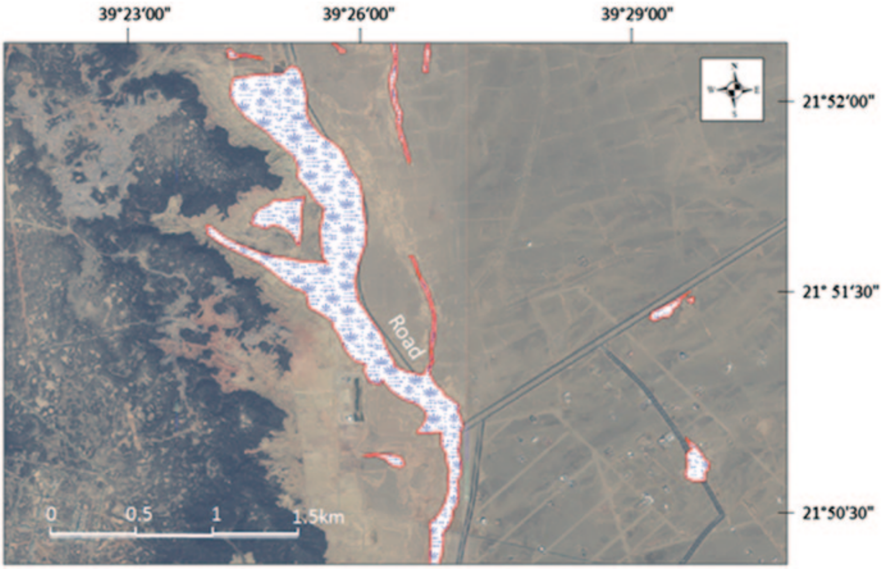

Fig. 9.21 Ikonos satellite image showing an example for locality No. 1, of the 3rd risk category. Flooded water runs along and over the road, notably the road was constructed in a watercourse

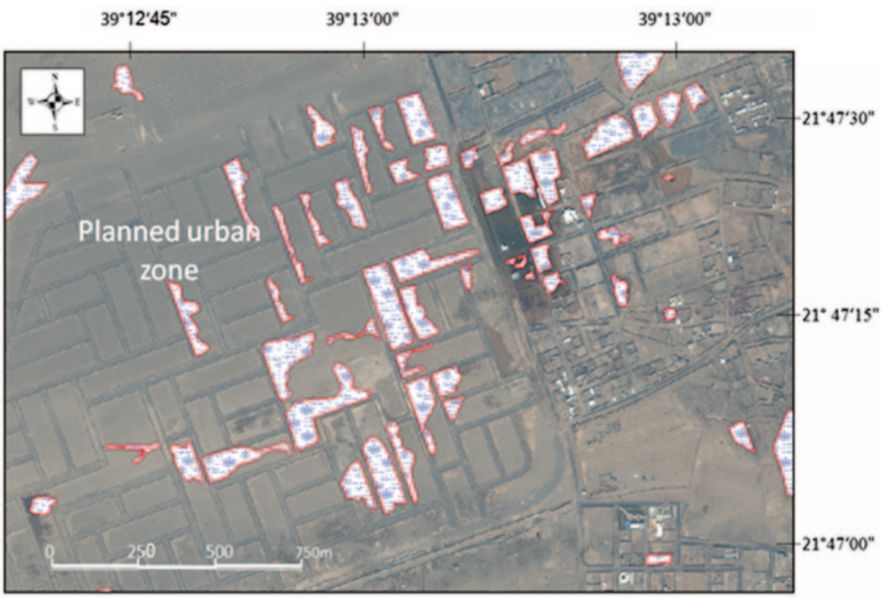

Fig. 9.22 Ikonos satellite image showing an example for locality No. 2 of the 3rd risk category. Flood water accumulated and shaped by the cement walls of the planned urban zone

Fig. 9.23 Ikonos satellite image showing an example for locality No. 3 of the 3rd risk category. Water accumulated in depressions and low-lands

Fig. 9.24 Ikonos satellite image showing an example for locality No. 4 of the 3rd risk category. Roads and routes shaped the flow aspects of running water

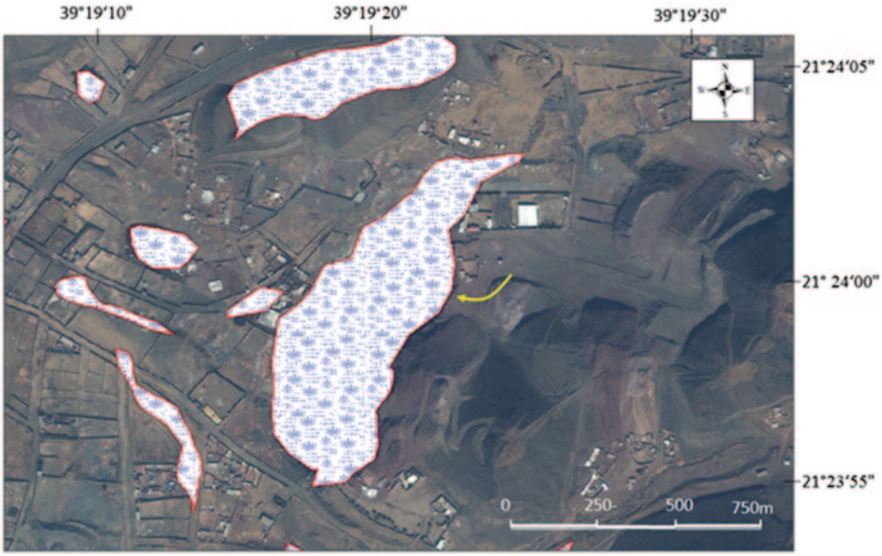

Fig. 9.25 Ikonos satellite image showing an example for locality No. 5 of the 3rd risk category. Stored water between consolidated rock masses

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Chapter 10
The Existing Flood Controls in Jeddah

Abstract Precautionary controls have been implemented in Jeddah area in order to reduce and mitigate the impact and risk of natural hazards. However, not all of these controls are effective for reasons of their scale, site selection and even engineering practices, among others. It is useful to investigate these measures after the event has taken place in order to induce their reliability and effectiveness. Such an investigation was carried out in Jeddah and the surrounding area following the floods and torrents that occurred in 2009 and 2011, and the effect of many of the controls implemented was found to be negligible.

For the achievement of construction projects, an integrated approach is usually taken which includes a set of tasks to be accomplished. These tasks include the construction of buildings to certain specifications and standards, accompanied by protective and precautionary measures, not only against floods and torrents, but to all aspects of natural hazards. However, in some instances protective controls are applied after the time of the building's construction, notably if the building has been subject to the effects of a natural disaster.

With regards to constructions in the Jeddah area, it is obvious that the structures, many of which are old, were built with little or no safeguards against natural disasters. This is a common phenomenon in many areas along the western Saudi coast. As a result, collapses, fissures and cracks are evident even in the most rigid constructions, which are not due to engineering structure itself, but rather to the lack of protection controls. Typical examples of this phenomenon are the roads, most of which were built to the specifications of international standards, but the absence of adequate protection for road-sides, for example, has resulted in the drifting and etching of these roads.

Applying this observation to floods and torrents, however, the obvious lack of flood controls in the area of Jeddah would not be found to be the main reason behind the severe damage that has been incurred. In this regard, controls not only exist in engineering practices, but may extend to legislation and environmental law that prohibit works that may exacerbate flood occurrence. It is clear from the analysis of satellite images, field surveys and the available data and reports that the flood controls that exist in the area of concern have different aspects and dimensions. These controls have a function with regard to other related physical processes, such as erosion, terrain sliding, etc. The situation in Jeddah can be addressed in the following

M. M. Al Saud, *Flood Control Management for the City and Surroundings of Jeddah, Saudi Arabia,* Springer Natural Hazards, DOI 10.1007/978-94-017-9661-3_10

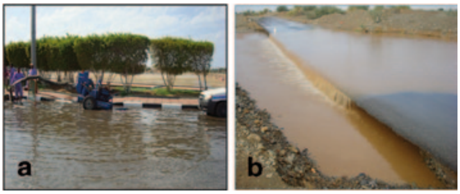

Fig. 10.1 **a** Absence of infrastructures. **b** Lack of small-scale tunnels

terms (1) absence of flood controls, (2) small-scale flood controls, (3) large-scale flood controls, (4) erroneous flood controls and (5) proposed projects and programs.

10.1 Absence of Flood Controls

This is the lack of required precautionary measures implemented to reduce and mitigate the impact of floods and torrents in areas which are at risk of such events. In their absence, the resulting damage will be high. The need to implement proper controls became urgent after the disasters of 2009 and 2011 took place.

Flood controls represent the most important protective measure. They involve:

1. Establishing infrastructures in urban areas to drain water, and maintaining the poorly implemented ones (example in Fig. 10.1a).
2. Stabilizing the territory of flood plains, and constructing retaining walls.
3. Constructing channels to divert water directly from valleys to the sea.
4. Reducing the flow energy along valleys by establishing dams and traces.
5. Cleaning and maintaining the existing storm channels.
6. Establishing tunnels with appropriate specifications to avoid overflow on roads (example in Fig. 10.1b).
7. Preventing encroachment on valley passageways.

10.2 Small-Scale Flood Controls

There are many small-scale (and sometimes medium-scale) flood controls[1] that are implemented by the private sector and sometimes by individuals. These are usually limited, of small dimensions, and relatively inexpensive; they are also mostly of short duration. However, the existence of such small-scale flood controls in several localities (i.e. on a frequent basis) acts positively in reducing the impact of damages. This small-scale application of flood controls is widespread in several regions of the world (Wernstedt and Hersh 2002).

[1] http://www.southholland.org/FMP/4-FloodControl2010.pdf.

Fig. 10.2 Examples on small-scale flood controls. **a** Small-scale drains. **b** Pipes for water tunneling. **c** Cement tunnel. **d** Al-Aakoom (soil embankment)

Even though small-scale flood controls exist only in limited areas, in many instances they have proved reliable in reducing flood damage. The major aspects of small-scale flood controls can be summarized as follows:

1. Small-dimension channeling and drainage systems along road-sides (Fig. 10.2a).
2. Constructing small-dimension tunnels, using either pipes or cement openings, notably along secondary roads (Fig. 10.2b, c).
3. Reducing the energy of water flow in valleys by creating small-scale dams and using rocks and soil embankments as obstacles (known as *Al-Aakoom*), as well as building traces (Fig. 10.2d).
4. Periodical cleaning and maintenance of the open channels, which is mostly done by the inhabitants.

10.3 Large-Scale Flood Controls

Usually, governmental sectors are responsible for the implementation of large-scale precautionary controls to reduce the impact of natural hazards, notably floods and torrents. These governmental sectors usually make the decisions about the nature of the required work and its geography and dimensions, and mainly depend on the results of scientific investigation and field observation when proposing the measures that need to be implemented. When the proposals for the projects are completed, they are introduced to contractors and companies who are expected to execute the work in accordance with agreed specifications and within a certain budget. It is clear that the precautionary controls (i.e. measures to reduce the impact of natural disasters) that exist in Jeddah and its surroundings were not implemented solely for the purpose of flood reduction and mitigation, but had multiple functions, such as avoiding land and construction instability, conserving cultivated lands, and other environmental considerations.

While large-scale flood controls in Jeddah and the surrounding area are sufficient to serve conservation purposes, the fact that there had been no remarkable torrential rainfall in the area for a couple of decades resulted in clear ignorance in implementing such protective measures. In addition, new anthropogenic challenges, especially chaotic urban expansion, have had a negative impact by increasing encroachment on the environment. The large-scale environmental controls that exist in the Jeddah area are inadequate in terms of number; in addition, many of these controls are not efficient enough to respond successfully to physical processes. Therefore, there are four large-scale flood control aspects in Jeddah area. The flood events of November 2009 and January 2011 played a pivotal role in indicating what controls needed to be implemented, and some of these controls are now in the process of being executed or in some cases, rehabilitated.

10.3.1 Old Water Channel "Storm-Water Drainage"

Water channels are usually presented by open concrete channels with a cross-section of a few meters, and may extended to several hundreds of meters[2]. This method of water control is widespread, notably for diverting flood water.

The project of water drainage in Jeddah, which is locally known as "*Storm-water drainage*", is considered essential in the region to reduce the impact of floods and torrents. This project, which was implemented more than four decades ago, demonstrates an integrated approach by experts who successfully considered both geomorphologic and hydrologic concepts.

The valleys extending from the mountains to the east of Jeddah open their outlets into the Red Sea. They follow a process of non-uniform run-off towards a wide coastal zone. The experts responsible for storm-water drainage realized that it was tedious to drain water from the mountains to the sea along each valley separately, even along channels; it made more sense to drain water from the mountains into an intersectional channel, which captures all running water routes into it at the same time. Then it diverts water to the sea along the two openings of the intersectional channel. This is the storm drainage that exists around Jeddah City. In other words, the storm-water drainage intersection crosses opposite to all valley (i.e. with different dimensions) passageways and joins all the outlets into a unique hydraulic system, which in turn conveys water to the sea.

The storm-water drainage comprises three major channel systems. They are named in this study (from north to south) as: Northern channel, Middle channel and Southern channel (Table 10.1 and Fig. 10.3). Each of the channel systems encompasses a number of conveying units (i.e. reaches), thus each one has its own dimensions and a separate discharge regime. Even though some of the reaches extend below the terrain surface, such as that of the Middle channel, all outlets into the sea.

[2] http://www.southholland.org/FMP/4-FloodControl2010.pdf.

Table 10.1 Storm-water drainages in Jeddah area

Channel (Storm-water drainage)	Total length[a]	General slope (m/km)	Average width	Average depth (m)
Northern channel	27.30	2.57	Variable	3–5
Middle channel	17.55	3.24	3.5 m	2.95
Southern channel	26.83	4.94	Variable	2.3–4

[a] As calculated from satellite images

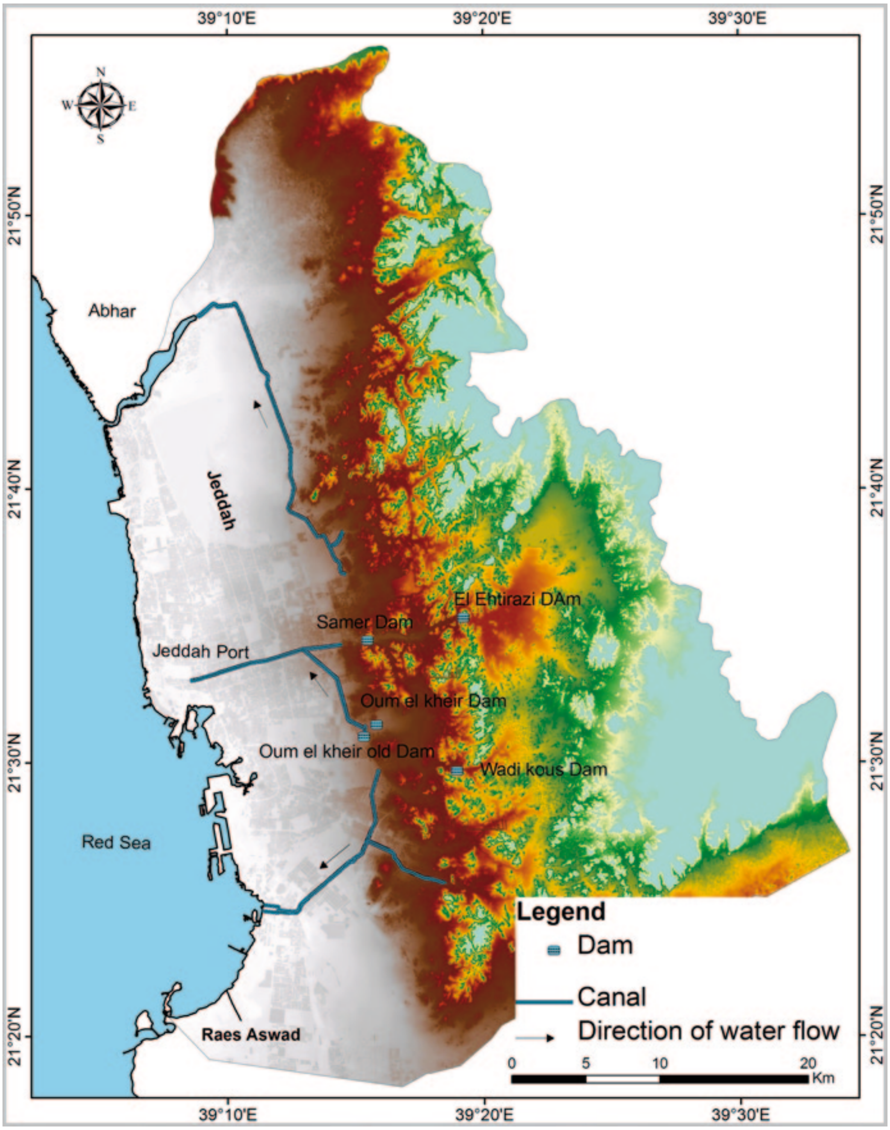

Fig. 10.3 The existing storm-water drainages and dams in Jeddah area

The total length of all the existing storm-water drainages is about 71.68 km, where the Northern channel is the longest with a length of 27.30 km (Table 10.1). The entire shaping of these drainages composes a ribbon of channels that extends around Jeddah City to protect it from non-uniform running water derived from the east.

10.3.2 Dams

Dams are usually built along valley courses in order to harvest the largest water volume, and then this water is utilized for various purposes, notably irrigation. Dams are also sometimes used as flood controls. A number of dams have been constructed along different valley courses in many regions of Saudi Arabia. These include King Fahed in Beisha (325 million m^3), Wadi Hala (249 million m^3), and Wadi Rabigh (220 million m^3) dams in Makka Al-Mukaramah, which are under construction, and Wadi Biesh in Jazan (193 million m^3) which is also under construction.

Following an integrated management approach, these dams are often constructed for several purposes. Notably, they work in restricting flood water, which can later be distributed among uniform channel systems instead of irregular overland flow on the terrain surface.

Accordingly, there are five major dams located in the Jeddah area, which are supposed to act in controlling the water flow that passes from the mountainous region to the sea through urbanized areas. Their role in protecting against floods and torrents is now of more concern than water harvesting. These dams were built at different dates, and some of them are still under construction at the time of this study. They are plotted on Fig. 10.3.

10.3.2.1 The Precautionary Dam

The Precautionary dam is situated in the mountainous region of Wadi El Assla, the second largest basin in the study area (289.4 km^2). It is located between the geographic coordinates: 21°35′18″N and 39°19′12″E, where it is bordered by Jabal Abou Rokaieba (285 m) in the south. According to the processed satellite images and field survey, the width of the dam cross-section is about 175 m, with 10 m height.

This dam was constructed in 2005, and it has an essential role in storing large volumes of water. It captured the flood water in November 2009 with a capacity of about 25 million m^3, as indicated by satellite images (Al Saud 2010). However, the dam shows some cracks following the torrential rainfall of January 2011, which has resulted in water leakage, and thus water needed to be released from its capacity.

10.3.2.2 Es-Samer Dam

This dam is located downstream of Wadi El-Assala, and in the north of Jabal Mriekh, and thus represents a contact point with human settlements. It is located 6 km from the precautionary dam, and extends in the geographic coordinates: 21°34′28″N and 39°15′28″E. The width of the dam cross-section is about 190 m, with 10 m height, also according to satellite images and field survey.

10.3.2.3 Omm El-Kheir Dam

This dam is located close to Es-Samer Dam at a distance of about 5.5 km. It extends between the geographic coordinates: 21°31′26″N and 39°15′48″E. The site of the dam is at the conjunction between two tributaries of Wadi Mriekh facing the Es-Samer urban zone. The width of the valley section where the dam is constructed is about 550 m, with about 10 m height. The purpose of this dam is to drain flood water in the Middle channel system, which is located in its proximity (Fig. 10.3).

10.3.2.4 Old Omm El-Kheir Dam

The old dam of Omm El-Kheir (out of use) is located several hundreds of meters away from the completed Omm El-Kheir Dam (Fig. 10.3). It extends between the geographic coordinates: 21°31′15″N and 39°15′22″E. The reason why the dam is not in use is due to the erroneous selection of the site, which is adjacent to Wadi Mriekh. It has a length of about 300 m facing the Es-Samer urban zone.

10.3.2.5 Wadi Kawes Dam

Wadi Kawes Dam is located in the downstream area of Wadi Kawes; it was built within the framework of an integrated project for Wadis Kawes, Methweb and Ghlil. It extends adjacent to the areas of Al-Massaad, Kowayza and Al-Racheed, within the geographic coordinates: 21°29′42″N and 39°18′57″E. These valleys mainly extend from Wadi Al-Khanek El-Shemali, Al-Harrazat and Wadi Ghlil in the east. The exact locality where the dam was built was subject to severe damage in the floods and torrents of November 2009. Satellite images show that the dam is situated in a narrow cross-section valley and between consolidated rock masses to the north of Jabal Al-Qourfaa (178 m). The width of the valley section at the site of the dam is about 200 m.

10.4 Erroneous Flood Controls

Even though the study area encompasses various forms of flood control, not all of these controls are effective and capable of protecting the locality where they were implemented. This is well evidenced by the degree of damage that has resulted from torrential rainfall; especially that which occurred in November 2009. Also, in some instances, some of these controls were subject to risk due to incomplete engineering structures. This was evidenced by the large amount of sediments and mud-filled channels, many of which have consequently collapsed, as well by cracking and many other failure aspects. This was prominent in the small and medium-scale controls, and it can be attributed to the fact that the flood controls in the Jeddah area were not implemented with sustainability in mind.

10.4.1 Examples of Erroneous Small-Scale Controls

As previously mentioned, some small-scale (and to some extent medium-scale) controls were implemented to protect against floods and torrents. These controls proved to be ineffective due to being in an inappropriate geographic position, due to the manner in which they were constructed, or because the specifications were not suitable. While most of them were not useful at all, they have served to motivate investigations into floods and torrents and more effective measures against them in the study area.

10.4.1.1 Depressions Dumping

This is a widespread phenomenon in the coastal zone, where people fill depressions and low-lands with sediments and rock debris in order to level the ground surface. Many other localities in the Jeddah region, notably the urbanized zones, are also dumped with unconsolidated sediments and soil accumulations.From a geomorphologic point of view, these depressions are normally known to accumulate rain water. However, dumping sediments and rock debris in these depressions will not allow water to accumulate and then the water will be drained irregularly on the terrain surface creating unfavorable routes (Fig. 10.4).

10.4.1.2 Closing Valley Passageways

In many localities in the study area, people close valley passageways using sediments and rock debris. This is done to either divert or collect running water into agricultural lands or to stop water movement over roads. Closing these valleys passageways results in negative impact when torrential rainfall occurs (Fig. 10.5).

Fig. 10.4 A depression where water accumulates in El-Marouh area. **a** Dumping the depression by sediments. **b** The same locality as observed from satellite images

Fig. 10.5 Closing valleys passageway by rock debris near Briman road

10.4.1.3 Soil Obstacles

After the events of 2009 and 2011, it was widely observed that inhabitants embarked on the construction of obstacles by accumulating soil, rock debris and sediments at different sites, notably in flat regions where wide valley-sections exist, in the belief that these would help in retarding water flow and thus prevent flood. However, these obstacles may fail and collapse when the volume of water becomes too great to be retained and then the bearing capacity of the accumulated sediments is overloaded. In this case, water will be rapidly released and may cause harmful damage (Fig. 10.6).

10.4.1.4 Narrow Tunnels

There is an inadequate number of tunnels, and the ones that exist were not built in the appropriate locations. Sometimes they are too narrow to drain water properly, especially when the water has a heavy bed load, and when they are filled by sediments the tunnels can become obstructed (Fig. 10.7).

Fig. 10.6 Obstacles put by inhabitants in a flat area of Wadi Ghaya adjacent to Al-Salhieh

Fig. 10.7 Narrow tunnel filled with sediments in Al-Qaraynah area

10.4.1.5 Tunnels in Erroneous Sites

There are also a number of tunnels of various dimensions that were built at erroneous sites, and consequently they have no role in organizing the water flow beneath roads (Fig. 10.8).

10.4.1.6 Bridges in Erroneous Sites

Many types of bridges have been constructed inside the study area, and also outside it, which are characterized by heavy engineering properties. While these cost a lot of money, the sites where they are located mean that they have a minimal role in protecting against the impact of floods and torrents (Fig. 10.9).

Fig. 10.8 Erroneous tunnel site, which must be at the low-level with respect to the road, but it was located at higher level of the road. Site is located in Al-Fadayalh area

Fig. 10.9 Large-scale bridge along small valley course, which has no useful application. Site is located to the north of Al-Basha'er area

10.4.2 Examples of Erroneous Large-Scale Controls

Small-scale (and medium-scale) controls can reduce damaging impact if there is a sufficient number of them. This is not the case with the large-scale controls that were previously mentioned. The flood and torrent damage of the last few years has clearly indicated that they are situated at erroneous sites. In order to remedy the situation, two major aspects must be considered: the geographic position and geomorphic and the hydrologic concepts, as well as engineering structures.

In many instances, the lack of success of flood and torrent controls is due to the fact that they were established temporarily and were not built with sustainable vision. Also demographic and climatic changes were not taken into account. For example, if urban zones extend adjacent to a dam, which has been constructed to mitigate flood impact, then the dam will lose its function. This is exactly what happened in the case of the old Omm Al-Kheir Dam.

10.4.2.1 Storm-Water Drainages

Man-made channels, with similar geomorphology to storm-water drainages (old channel) have proved efficient worldwide, in areas where water from elevated regions flows towards the coast passing through urban zones. Examples are the Santa Rose channel in California, Alameda Creek channel in Auckland and the channeled Tijuana river in Mexico. From a hydrologic perspective, the storm-water drainage in the Jeddah area, with the three channels system, is similar to these made-made channels. Such a drainage system captures all water outlets from the mountainous

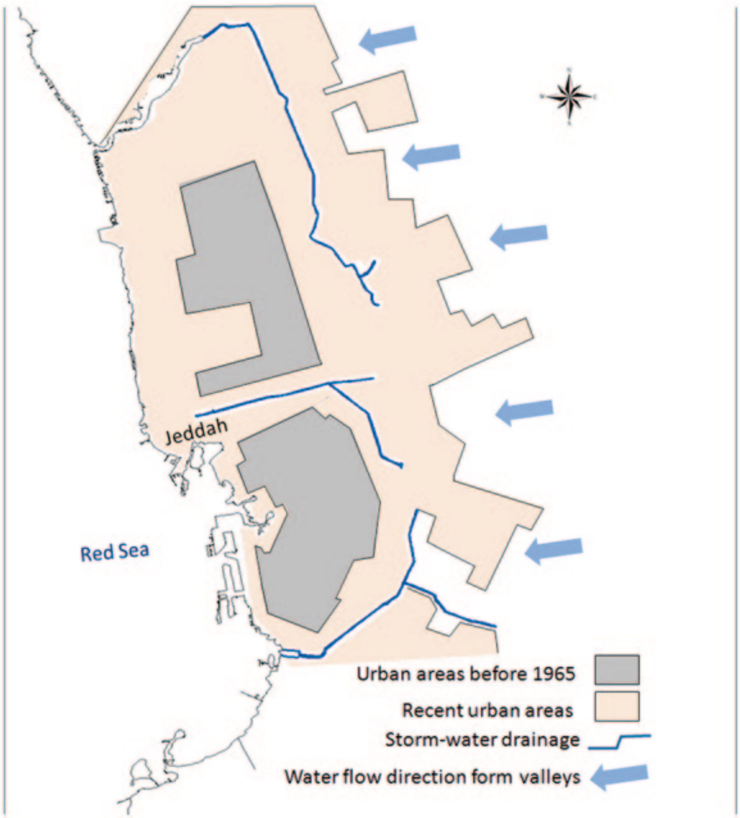

Fig. 10.10 Schematic figure showing storm-water drainages with respect to the previous and recent demographic changes

region and channels them to the coastal zone. However, after 45 years of performing this role, urban expansion has interfered with this drainage system, meaning that storm-water drainage has become included within urban areas rather than going around them. This results in negative impact on the conveyance of water due to demographic changes in the region. This is shown in Fig. 10.10.

The resulting environmental situation of this artificial drainage can be summarized as follows:

1. Urban encroachment has canceled the role of the storm-water drainage.
2. There is an obvious lack of periodical follow up, including the removal of sediments, maintenance, etc.
3. Excavation work in the proximity of the storm-water drainage has caused cracking in many parts of its channel, which has resulted in water leakage in many localities.
4. Many reaches of the drainage have become sites for the disposal of solid and liquid waste, which has retarded water flow, as well as causing environmental problems.
5. According to the hydrologic parameters, and as shown in Table 10.1, the general slope gradient of the existing channels is relatively low (i.e. between 2.57 and

4.49 m/km). This results in low energy flow, and thus decreases the discharge rate from the outlets, as well as increasing the evaporation process.
6. Yet, there is an absence of environmental legislation to protect the areas that surround the channels.

10.4.2.2 Convey Channels

Given that the role of storm-water drainage in conveying water towards the sea has been curtailed by urban expansion, convey channels have now been established that join some valley courses that are located adjacent to urban areas with the storm-water drainage.

Recent implementations to convey water between valley courses and the old channel (storm-water drainage) are represented by:

1. Briman convey channel between Wadi EL Hatiel and the storm-water channel.
2. The convey channel from Es-Samer Dam to the storm-water channel.
3. The convey channel from Omm El-Kheir Dam to the storm-water channel.

From a hydrologic perspective, convey channels are useful systems for draining water, especially since the storm-water drainage has become non-functional and needs re-investment. However the conveyance mechanisms between valleys in the mountainous region and the storm-water channel were implemented without proper consideration of hydraulic aspects. The convey channels have different dimensions than those of the storm-water channel the cross-section area of the convey channels is larger than that of the old channels, and thus the loaded volume of water and sediments is greater than the capacity of the storm-water channel, resulting in overflow during torrential rainfall events (Fig. 10.11).

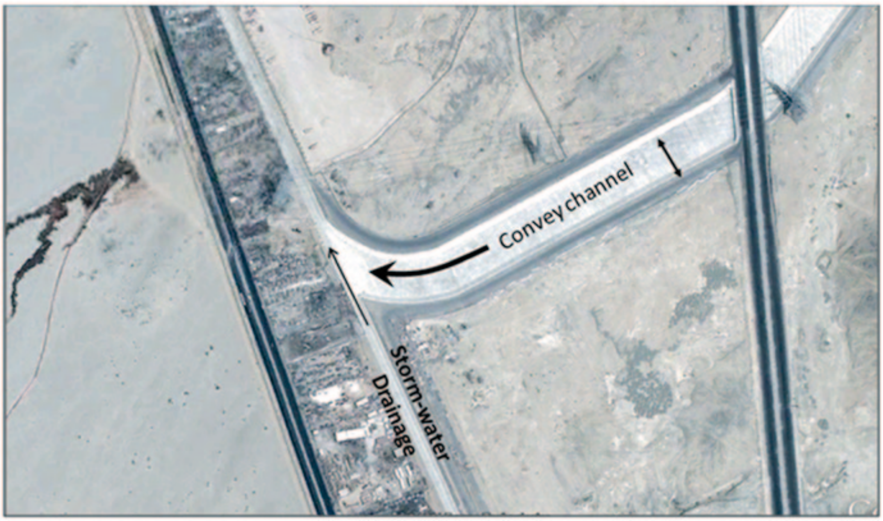

Fig. 10.11 Satellite image (Ikonos) showing the newly executed convey channel and the storm-water drainage with different dimensions at Wadi El Hatiel

10.4.2.3 Dams

Dams control large volumes of water flow and retard the energy of water masses, and can thus play a role in reducing the impact of floods and torrents. However, dams can also play a negative role when they have been constructed on the wrong site or the structure has not been consolidated. In these cases, dams have frequently been known to collapse, causing severe damage to the surrounding areas due to the sudden release of large amounts of water. This was recently witnessed in Qanouna Dam in Al-Konfoda Caza[3].

When a dam collapses, the engineering companies that constructed the dam are usually held responsible; more specifically, the fault is held to lie in the engineering structures of the dam itself. However, dams can also collapse and/or crack due to the geographic location where they were built.

This is often the result of ignoring geologic and geomorphologic parameters while selecting dam sites. Since the collapse and failure of dams results in severe damages to the neighboring urban and even agricultural areas, it is of the utmost importance to construct dams in localities away from urbanized zones.

1. *The Precautionary Dam*:

The construction of the Precautionary Dam between consolidated rock masses makes it of high rigidity, due to the lithologic characteristics of the existing rocks. However, the rock deformations in this locality make it an unfavorable site even if the engineering structure of the dam is correct. The Precautionary Dam stored about 25 million m^3 of storm water after the torrential rainfall of November 2009 (Al Saud 2010); otherwise, the area downstream of Wadi El-Assla would have been severely damaged. Even though it played an essential role in retarding water flow towards the urban zones downstream, the author pointed out the unfavorable situation of this dam (Al Saud 2010). That is because the dam is situated exactly at the intersection between two major faults. This may cause the displacement of lateral and vertical tectonic movements along these faults (Fig. 10.12).

The Saudi Geologic Survey Organization[4] attributed the cracks that were recently observed in the walls of this dam to its engineering structure, and consequently concluded that the bases of the dam were not deep enough to reach the bed rock.

On the basis of satellite image analysis and field verification in this study, the problems with this dam can be attributed to:

1. The locality of the dam in an erroneous geological setting (Fig. 10.12).
2. The unfavorable engineering structure, according to the Saudi Geological Survey.
3. The absence of boundaries around the lake that was located beyond the dam in order to conserve the stored water.

[3] http://forum.arab-mms.com/t368863.html.

[4] http://ksa.daralhayat.com/ksaarticle/229216.

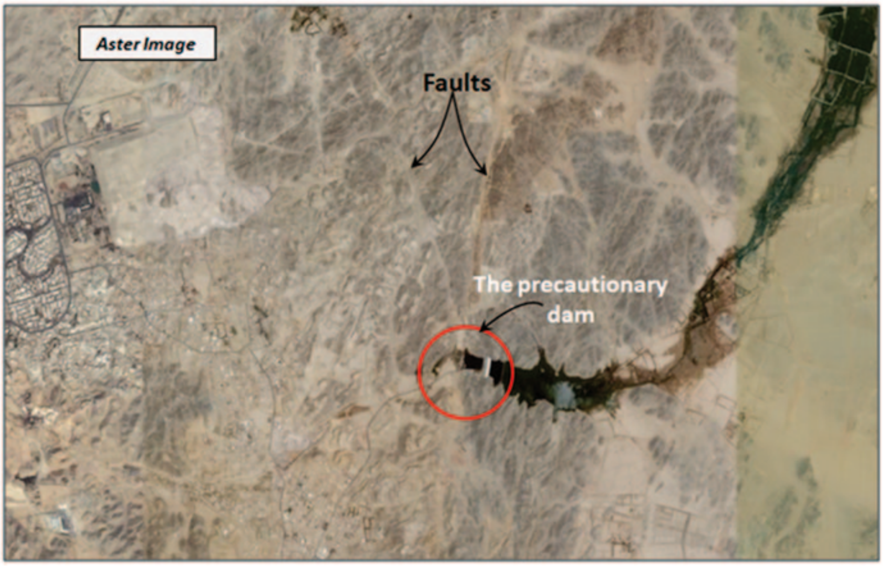

Fig. 10.12 The location of the Precautionary Dam at the intersection between two faults

2. *Es-Samer Dam*:

Es-Samer Dam shares similar characteristics to the Precautionary Dam. It is located along the Wadi El-Assla watercourse and away from the Es-Samer urban zone by a distance of about 300 m. This dam has been classified in the 1st risk category (Table 9.1 & Figs. 9.4 and 9.5). It was clear from the DEMs analysis that the dam is situated between narrow mountain hills, which can result in water injection towards the urban areas in the event of any collapsing that may occur.

The existing implementations show that the dam will act as a reservoir to store running water from the upstream area, and this water will be released uniformly along the convey channels (closed cement pipes), which is, in general, a correct hypothesis. The depth of the dam does not exceed 10 m, and the wall facing Wadi El-Assla is constructed from concrete, while the inner wall facing the urban zone is constructed from compacted rock masses all over the valley cross-section, which is around 190 m width (Figs. 10.13 and 10.14).

Considering the geomorphologic parameters, the following errors are encountered with regard to Es-Samer Dam:

1. The water level is relatively shallow with respect to the valley length and to its cross-section; therefore, a large volume of volume may be accumulated and consequently overflow may occur (Fig. 10.13).
2. The construction of the dam close to the urban zone makes this a risky locality, especially since the geomorphologic characteristics show that its situation makes it susceptible to the collection of a huge volume of water; therefore any failure in the body of the dam will result in damage to the adjacent urban zone.

Fig. 10.13 Photo of Es-Samer Dam showing its depth from the urban zone side

Fig. 10.14 The convey channel and the cross-section of Es-Samer Dam

3. The width of the convey channel is about five times larger than the old channel (storm-water drainage), and this is in direct proportion with its capacity. Hence, any overloaded volume of water from the dam to the convey channel will not be totally captured by the old channel.
4. The shallow depth of the convey channel may result in the water level rising over the flanks of the channel, and this will also impact on the neighboring urban zone.

5. The closed cement pipes are usually used to outlet sewage water, and more specifically water with no heavy bed loads; therefore, they are not suitable to drain storm water. However, this was how they were used in the Jeddah area, where the mountainous regions are adjacent to urbanized zones and these regions contain a predominance of friable sediments and sand, as well as being vulnerable to erosion. The consequence is that drifted materials and debris may clog these closed cement pipes.

3. *Omm El-Kheir Dam*:

Omm El-Kheir Dam was built according to the same concepts as Es-Samer Dam. It is located at a valley outlet of Wadi Mriekh, and also in proximity to the urban zones. However, it differs from Es-Samer Dam in that Omm El-Kheir Dam has a small catchment area; it was therefore classified in the 2nd risk category. The cross-section of the valley, where the dam is located, is relatively wide and was estimated at 550 m. In addition, the dam was constructed on one of Wadi Mriekh's tributaries, whilst other tributaries are still untrammeled (Fig. 10.15).

Water storage behind the dam follows the same mechanism as that at Es-Samer Dam, where collected water is released along open channels, and then connected to the old storm-water channel by closed cement pipes.

The site selection of this dam is also considered to be erroneous, due to unfavorable geomorphologic and hydrologic parameters. These are as follows:

1. The maximum water level of the dam is shallow in relation with the width of the valley cross-section, which is supposed to carry large amounts of water and sediments (Fig. 10.16).

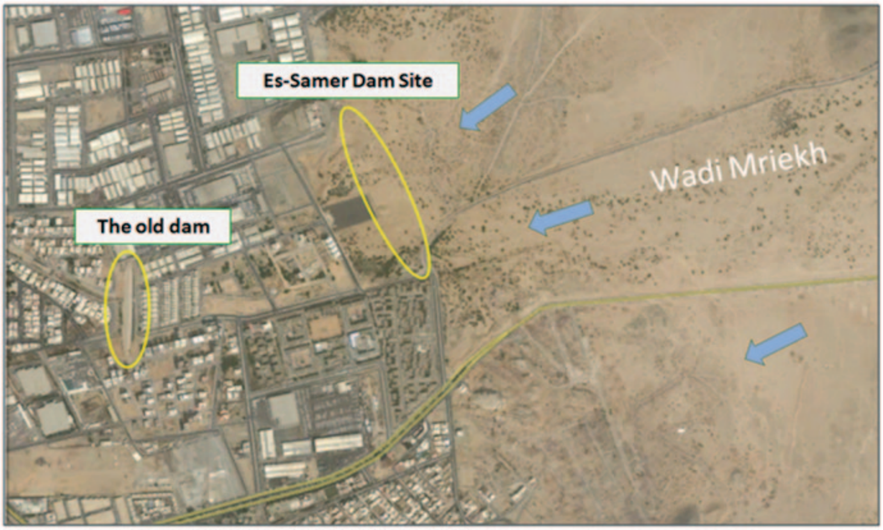

Fig. 10.15 Omm El-Kheir Dam as observed from satellite image (Ikonos), which also shows the old dam

Fig. 10.16 The depth of Omm El-Kheir Dam as appears from Wadi Mriekh side

2. There is another tributary close to the site of the existing dam, and the outlet of this tributary still opens next to the urban zone, which puts the zone at risk (Fig. 10.15).
3. The location of the dam adjacent to the urban zone presents problems as any failure or collapse may directly impact on this zone.
4. Similar to Es-Samer Dam (since the same company was responsible for its construction), the depth of the conveying channel is shallow, and closed cement pipes are used in the joining with the old channel, which is also an erroneous procedure.

4. *Wadi Kawes Dam*:

In this study, the site of Wadi Kawes Dam is classified in the 1st risk category because the neighboring areas were witness to severe damages in the floods and torrents of November 2009. This damage also extended to remote regions along the outlet of Wadi Kawes, due to the non-uniform water flow along roads and channels. The main reason why this valley is at risk is that it joins a number of other valleys which then outlet into a narrow and meandered valley section (where severe damage has occurred). This is clearly evident from the DEMs in Fig. 9.10, and the map of Fig. 9.11.

In terms of the geomorphic and hydrologic parameters, water at the site of this dam is expected to be injected with high energy, which is what happened in November 2009. In addition, from field reconnaissance it was clear that several construction activities (e.g. buildings, oil stations, etc), have been instigated in the valley passageway in recent years (after November 2009), thus ignoring all the above mentioned precautions. This is what can happen in the absence of environmen-

Fig. 10.17 Closed cement pipes to convey water from Wadi Kawes Dam to the old storm-water channel

tal legislation. While it shares similar erroneous aspects to those of Es-Samer and Omm El-Kheir dams, Wadi Kawes Dam is different in that it is located at a distance of about 4 km from the old channel (storm-water drainage). The convey process between the released water from this dam and the old channel is along closed cement pipes (rounded pipes) as shown in Fig. 10.17.

The accumulated water behind this dam gives sediments and rock debris the chance to settle before any draining takes place into the closed pipes. However, this can also create problems since the water released from the dam will contain a considerable amount of sediments. This, along with the gentle slope gradient of the closed pipes, will dropdown the loaded sediments into the pipes over the four kilometer length, since the estimated (from the DEMs) slope gradient between the dam and the old channel is about 6 m/km, which results in low-flow energy and gives sediments a chance to deposit in the closed pipes.

10.5 Proposed Projects and Programs

The issue of floods and torrents was not given serious consideration before areas lately became witness to severe catastrophic events. Following this, the need to implement flood controls and other precautionary measures was recognized in order to reduce or mitigate this environmental problem. Hence, it was proposed that other actions be taken in addition to executive flood controls (e.g. the construction of dams, channels etc). These actions were described as "*Rapid Solutions*", indicating that their urgent implementation was needed.

10.5.1 The Rapid Solution

In response to the floods and torrents that occurred in the Jeddah area, but covering the wide framework of the Saudi Kingdom, the Secretariat of Jeddah city has formulated an integrated plan to be implemented over 3 years by the ICOM International Company. This includes rapid solutions which were proposed in the PSM Contracting Document to be applied at 12 critical sites. It was proposed that these be implemented within 6 months.

The focus of the rapid solutions is on the infrastructure of the coastal zone. However, an integrated water drainage system is also needed, especially in the absence of comprehensive and proper infrastructural water systems. Hence, if both geomorphologic and hydrologic parameters are considered, there must be two approaches to the control of flood water. There must also be differentiation between the hydrology of the coastal zones, especially with regard to the internal part of the coast, and the elevated zone. That is to say, water flow in the mountainous regions follows a definite regime whereby water runs along the sloping terrain and impacts with urban zones, as happened recently resulting in severe damage. On the other hand, the coastal zones have no remarkable water flow; water reaches the terrain surface directly from rainfall and usually has very low impact.

According to the above discussion, solutions must primarily be applied to the sources of derived flood water in the mountainous regions and not to the adjacent regions, even though the latter need to be protected. In other words, rapid solutions should be applied to the influencing localities, which exist in the mountain chains, and the solutions will not be comprehensive and perfect if they are applied separately in the coastal zone, which also needs flood control systems.

10.5.2 The "Natural Disasters Management Center"

Other aspects of the rapid solutions implemented after the floods and torrents that took place in Jeddah (2009 and 2011) focuses on the urgent rescue of people from the damaged areas, as well as the investigation of all details of the disaster. For this reason the Natural Disasters Management Center was established, which aims to aid inhabitants in the destroyed localities as soon as the disaster takes place. It also aims to monitor approaches whenever floods and torrents occur in Jeddah[5].

The main remit of the Center is to forecast and monitor, rather than to implement precautionary measures. This is done by the coordination of different civil and military sectors through the use of the most advanced tools of audio, visual and other communication. Helicopters and around 150 monitoring cameras are utilized to transmit images and real-time data.

[5] http://www.alwatan.com.sa/Local/News_Detail.aspx?ArticleID=66135&CategoryID=5.

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Chapter 11
Required Controls for Floods and Torrents in Jeddah Region

Abstract When the geographic extent and behavior of a natural hazard are determined, the resulting damages can be well identified. This helps decision makers in selecting the most appropriate controls to be applied in order to reduce the level of risk. This study investigates the fundamental flood and torrent controls that exist in Jeddah area. These controls were classified on three levels, depending on terrain characteristics and water flow behavior. While some of these controls have been recently implemented, there are still a number of major protective measures that need to be taken.

The aspects and dimensions of flood and torrent controls, and approaches to the reduction and mitigation of these events often vary between regions, between countries, and even between different regions of the same country. Flood controls are governed by several physical and anthropogenic parameters, as well as by socio-economic parameters, although the protection of human life remains the priority. Moreover, natural hazards usually become an issue of concern after the events have taken place; especially if they have resulted in severe damages. It is important to select the appropriate measures and tools for flood reduction and mitigation, basing this selection on precise scientific data and information, as well as on field surveys in the damaged areas. By these means, lessons can also be learned with regard to which controls are successful and which are not.

The flood and torrent controls for the Jeddah area, as proposed in this study, are based on the diagnostic analysis of the physical and anthropogenic parameters that exist in the area, as well as on the investigation of the different dimensions and aspects of the damaged areas. This will lead to the appropriate selection of flood controls. It will also become apparent that different scales of flood controls need to be adopted rather than considering large-scale ones as a separate solution.

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11.1 Small-Scale Flood Controls

These are precautionary measures that can be implemented by individuals who live in zones at risk of floods and torrents. They are usually cheap and can be achieved by using simple tools that are available locally. These controls have been deduced by replicating mechanisms which have been widely applied in different regions worldwide and proved efficient in reducing the impact of floods, even though at a local scale. Some of them, rather than dealing directly with the issue of running water, involve controlling land stability, that is, the soil and soft rocks over which the water flows. In addition, small drainages are built to drain water into minor routes and streams, notably if the terrain surface controls water flow and results in irregular run-off.

11.1.1 Fixing Weights

This aspect of small-scale flood controls involves the use of heavy weights to fix friable materials on the terrain surface including mainly sand, soil, and sediments. These loose materials closed many valley passageways in the Jeddah area during the floods of 2009 and 2011, and their accumulation caused the water level to rise, leading to flooding and damage in the surrounding regions. To prevent this from happening, "Sand bagging" is usually used to stabilize the flanks of watercourses and the flood plains of valleys, especially those situated close to urban areas. Sand bagging involves stacking up sackcloth bags filled with sand. There are several technical specifications to be considered when selecting this type of this small-scale flood control[1]. The most important are:

- The selection of an appropriate site, which must not be too close to the buildings in order to avoid any impact on the bases of these buildings.
- There must be no isolators between these bags and the ground where the bags will be fixed, because this will cause the bags to slide out of place. The bags must not be positioned on sloping surfaces.
- A technical approach must be adopted in implementing this type of flood control in order to ensure its effectiveness. For stability, the bags need to be stacked on each other in a vertical accumulation as shown in Fig. 11.1. Thus, it is recommended that the width of the accumulated bags is three times bigger than the height.
- The base of the sand bags should be fixed to an excavated and rough terrain surface to ensure tight joining with soil and rocks (Fig. 11.1). In addition, a certain method needs to be employed in filling the bags: they should only be filled to about 50 % of their capacity, and they should be securely fastened.
- In the case that such bags are not available, rock masses can be used instead. They should be securely fixed to the terrain surface in a pyramidal and intervening

[1] http://www.ag.ndsu.edu/pubs/ageng/safety/ae626w.htm.

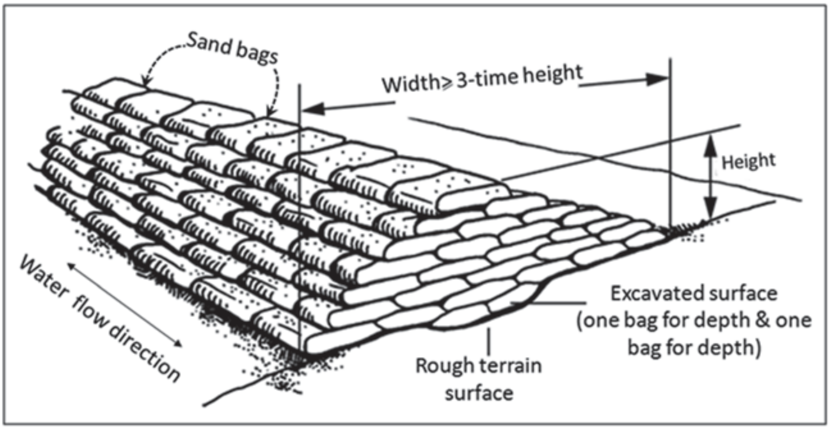


Fig. 11.1 Schematic figure showing the recommended dimensions for sand bagging

shape. Figure 11.2 shows typical sites that may be selected for sand bagging. However, selecting the exact site remains a matter of field investigation and depends on where the inhabitants need the flood control.

11.1.2 Retaining Walls

Another precautionary measure is the construction of concrete walls along road sides and watercourses, notably those which are not stabilized in order to fix these sides and avoid erosion processes.

Many aspects of the damage following the floods and torrents in Jeddah were the result of terrain failure and the collapse of unprotected constructions including buildings, walls and roads. In addition there was severe drifting during the flood events which led to the complete closure of roads, as was the case in Wadi El-Mouhrq (Fig. 11.3).

Figure 11.2 shows typical proposed sites for the construction of retaining walls in the Jeddah area. Detailed engineering specifications for these walls are determined according to the characteristics of the local terrain and the following items must be considered:

1. Retaining walls must be constructed on ridged terrain, and in cases where such terrain is lacking, the depth must be increased according to the proper geometric parameters.
2. "Opening holes" must be made in the walls' sides in order to outlet the water retained behind the wall.
3. The height of the wall must be above horizontal constructions such as roads, and must not be less than 1/3 of the height of vertical constructions such as buildings.
4. The terrain on which the wall is to be constructed must be considered. If the terrain is wet and unconsolidated (e.g. sandy, muddy, etc), Gravity or Cantilevered

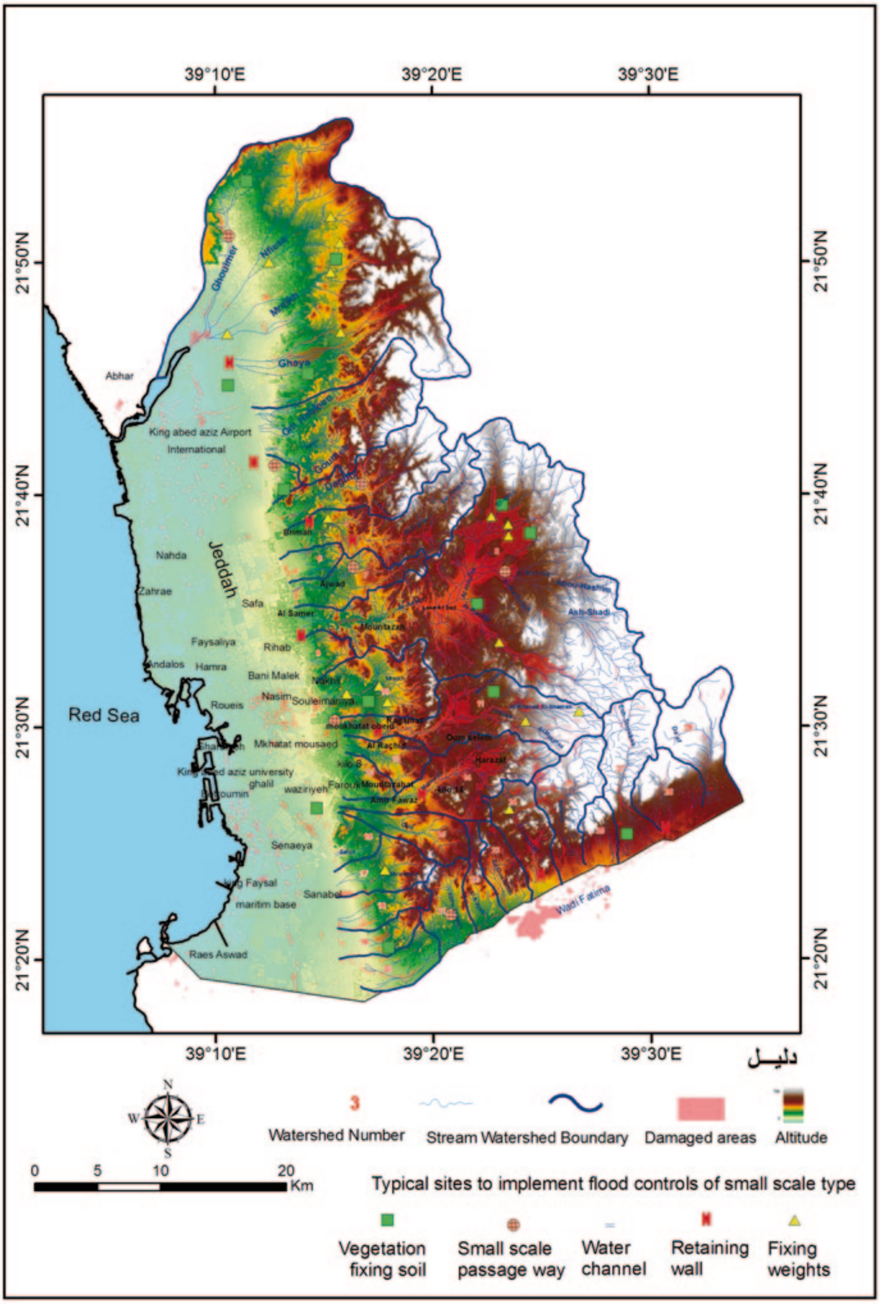


Fig. 11.2 Proposed typical sites to implement small-scale controls for floods and torrents in Jeddah area

Fig. 11.3 Lateral etching of terrain materials along roads due to the lack of protection works

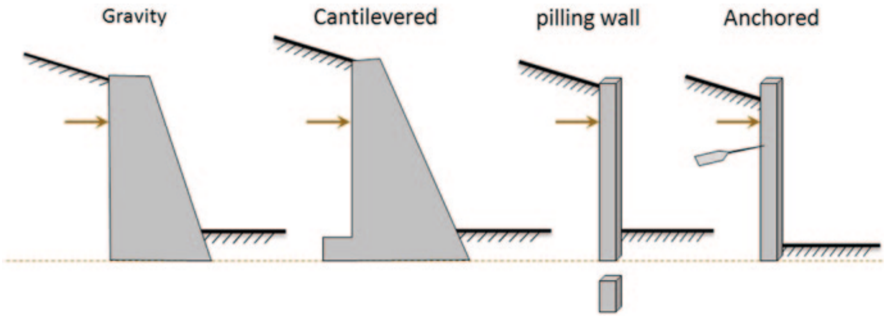


Fig. 11.4 Geometry of major types of retaining walls

walls should be constructed. If the terrain is solid, it is preferable to construct Pilling or Anchored walls (Fig. 11.4).

11.1.3 Open Channels

Open water channels are "water drains" with small-scale dimensions. They are constructed by excavating the terrain surface, and then embanked by cement or stones. This measure has been widely employed in the area of concern, with positive results. Open channels usually have a depth of less than 50 cm, and a width of less than 1 m (see fig. 10.2a, Chap. 10). They usually have a hemispheric shape or V-shape in order to enhance water flow. Such small-scale controls can be implemented by individuals since they do not cost too much; especially if natural rocks are used in the execution.

The appropriate parameters should be considered in the construction of these channels; thus it is necessary to consider the slope direction of the running water. This can be identified from the flow direction of water after periods of rainfall. In addition, the connecting systems should be well executed; the connection between these channels must have open angles, and the outlets should also be identified. The typical sites for these channels are proposed in Fig. 11.2.

11.1.4 Small-Scale Tunnels

These are rounded tunnels with relatively small diameters used to drain water. They are usually built beneath small roads where watercourses cut across these roads. Different concepts are applied to these tunnels with respect to the retaining walls. Tunnels are implemented where water runs across roads, while retaining walls are implemented where water flows parallel to road alignments. The following points must be considered:

1. That the road width is consistent with the tunnel length.
2. That the concavity (i.e. bending) of the road is consistent with an increase in the diameter and number of the tunnels.
3. That the cross-section of the watercourse is also consistent with the diameter and number of the tunnels.

In addition, many engineering specifications must be followed for the proper construction of these tunnels. Rounded cement pipes, or preferably pipes confined in concrete are used in order to preserve their rigidity (Fig. 11.5). Also, putting steel networks at the openings of these tunnels to avoid their closing is not recommended. Figure 11.2 shows the typical sites for these tunnels in the study area.

11.1.5 Stabilizing Terrain Surface by Vegetation Cover

This is a well known procedure which is usually applied within the framework of integrated projects concerned with developing the agricultural sectors, improving the landscape and fixing unstable territories (Fig. 11.6). This approach has played an essential role in the area of study, notably in the area located in Wadi El-Meri, north and east of the former El-Mesek Lake.

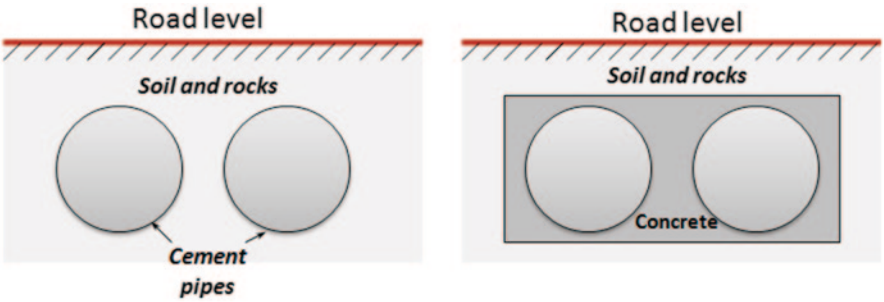


Fig. 11.5 Selected types of small-scale tunnels

Fig. 11.6 Example on plantation projects to stabilize terrain surface near Wadi El-Meri

To stabilize the terrain surface, shrubs with vertical-extension roots are planted where unstable and well-bedded terrain exists, while shrubs with horizontal-extension roots are planted in unconsolidated terrain. The extension of these roots serves to join and thus stabilize different terrain components and consolidate them as one unit. Figure 11.2 shows proposed typical sites for this approach.

11.2 Medium-Scale Flood Controls

These are also precautionary measures of moderate dimension implemented to reduce or mitigate the impact of floods and torrents. If these controls are executed properly (i.e. all aspects of medium-scale ones with sufficient number), they are able to completely prevent the impact of floods and torrents. The implementation of these controls is often the responsibility of governmental sectors, who assign the projects to appropriate companies. In addition, these controls are mostly implemented at defined sites, and their expenses are moderate depending on the scale and nature of the work to be done.

The medium-scale flood controls proposed in this study can be applied according to the differing conditions that exist between regions applied according to the differing conditions that exist between regions. In addition to the physical and environmental factors, other factors may come into play, such as private ownership, land use, etc.

11.2.1 Check Dams

These are relatively small dams which are usually constructed along streams and secondary tributaries. The geomorphologic setting of their localities determines their dimensions. However, it is common that the width of these dams does not exceed a few meters. In this case, a bore is excavated at the site where the dam is to be built. The wall (which must not exceed in height two times the bore depth) is executed beside the bore, and then the bore is embanked by concrete or stones (Fig. 11.7).

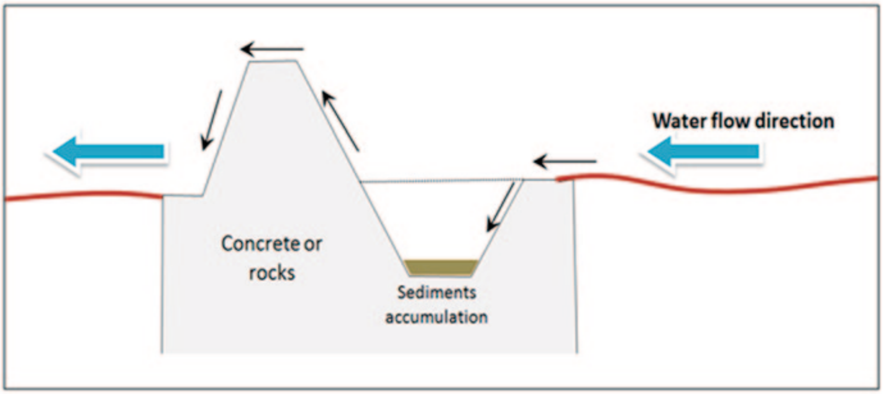


Fig. 11.7 Example showing a cross-section of a proposed Check Dam

These dams have many functions, including acting to reduce water flow energy, water bulk, and the volume of eroded materials and transported sediments. Usually, the accumulated sediments in these dams are measured to calculate erosion and sedimentation rates; this is why they are called “check dams”.

In order to reduce water flow energy, terrain bores are often executed; of an elongated shape and crossing the flow direction of watercourses, the sections of these bores act as dumping terraces that capture the transported sediments and retard the flow velocity. Figure 11.8 shows typical sites proposed to construct these dams in the study area.

11.2.2 Valley Obstacles

When torrential water impacts on urban settlements, the damage level increases in line with the increase in flow energy. This was dramatically evidenced in November 2009, when turbid water ran at high energy, sweeping up objects in its path, including rock debris and cars, and transporting them to remote localities. Had the water flow energy been slower or the flow more calm, considerably less damage would have occurred. The above mentioned check dams, and soon to be discussed valley terraces are controls that act to reduce the flow energy of water. While valley obstacles are not commonly used, they are put forward here as a means of flood control. As proposed in this study, they would be composed of large rock masses, of consolidated and resistible type, or alternatively they could be concrete masses. These masses would be positioned in valley passageways where water often has a high flow rate. Such valleys have become well known in the study area, notably those which are characterized by thick sediments and sand, namely Wadi El-Mouhrek, Wadi El-Mazabeh, Wadi Kawes and Wadi Methweb. When water impacts with

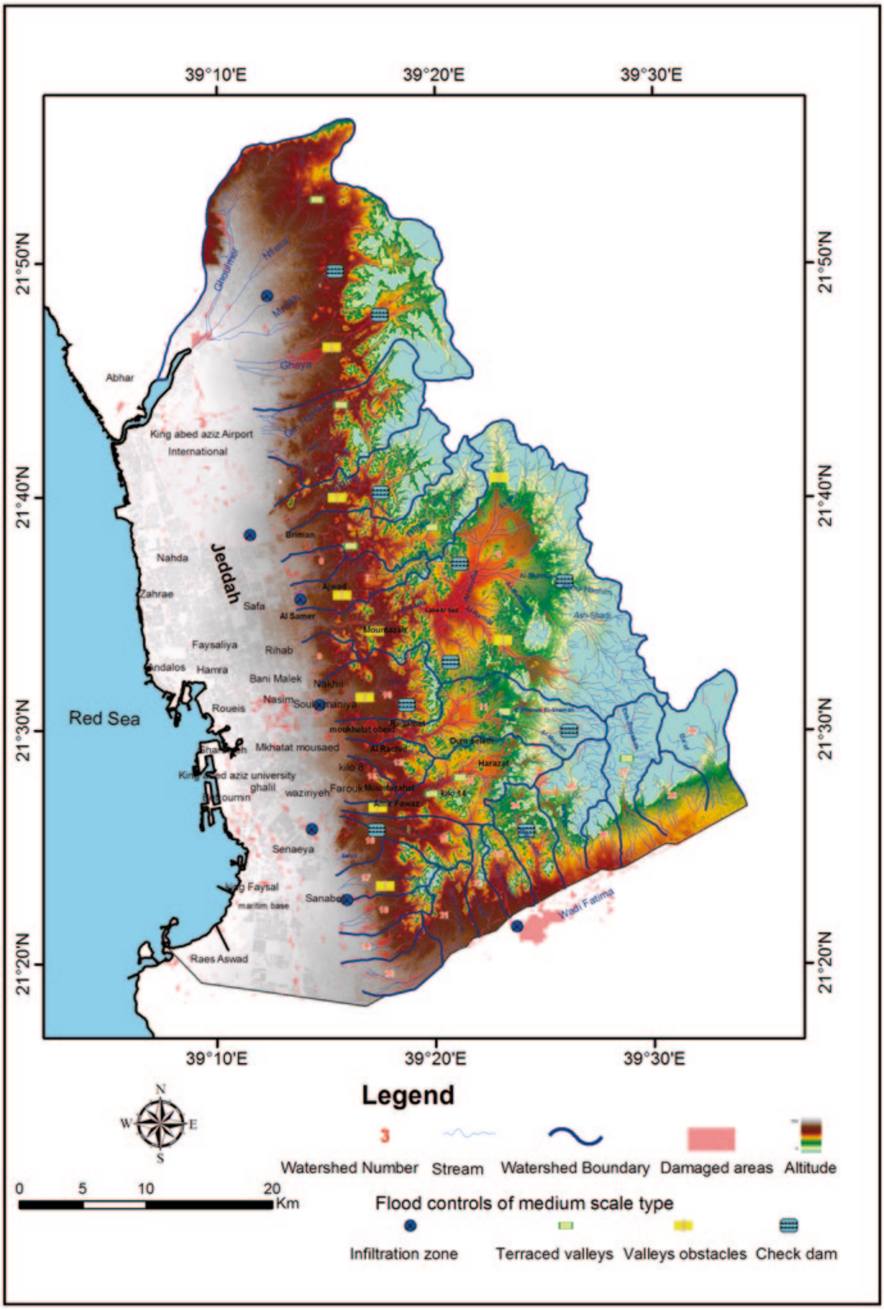


Fig. 11.8 Proposed typical sites to implement medium-scale controls for floods and torrents in Jeddah area

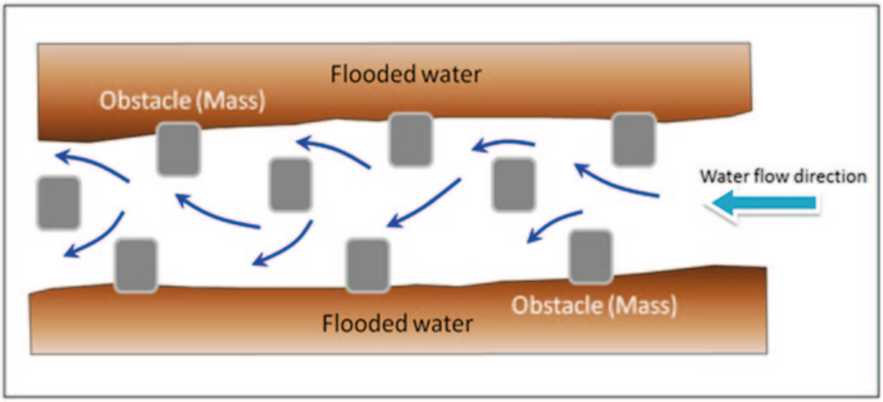


Fig. 11.9 Plane view showing the scheme of proposed valley obstacles

masses positioned in these valleys they will act to retard water (and sediment) flow energy (Fig. 11.9). However, this practice of putting obstacles in valleys may create problems, and needs to be carefully studied. The obstacles should be at a specific distance from each other and comprise an intervening scheme (Fig. 11.9). Figure 11.8 shows the typical sites proposed for valley obstacles in Jeddah and its surroundings.

11.2.3 Valley Terraces

Referring to geomorphologic concepts, an increase in channel slope will result in an increase in channel depth, forming narrow valleys which in turn accelerate water flow. The presence of urban settlements among these valleys will result in severe damages. In Jeddah and the surrounding area, similar to many other regions worldwide, terraces are constructed along narrow valley courses. These terraces are composed either of concrete or rocks, which are built in a gradational scheme (Fig. 11.10). Such terraces act to reduce water flow energy and thus also any negative impact.

Fig. 11.10 Example of the proposed valley terraces

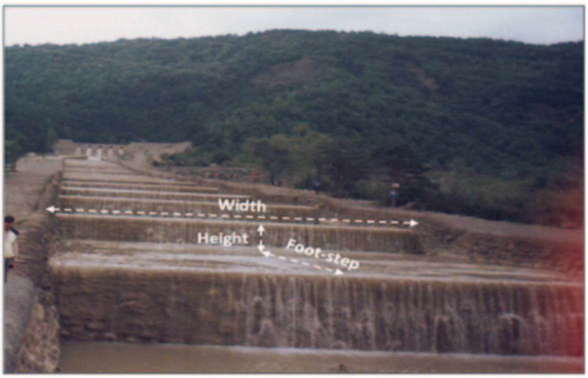


Fig. 11.11 Road cut by torrents, and a scheme of a proposed bridge

With regard to the dimensions of these terraces, the width should be the same as the valley width, while the foot-step should be two times the height of each terrace. The use of DEMs is useful in determining the proper sites where these terraces should be constructed. Figure 11.8 shows typical sites for these terraces in the study area.

11.2.4 Bridges

The protection of human life is given priority in the implementation of flood controls, and preparations should be made for their rescue in the event of natural disasters. Lack of such preparation has led in many instances to increased casualties and loss of life, as was the case during the floods and torrents that recently took place in the Jeddah area. It is imperative that transport routes such as roads, bridges etc are always accessible and kept in an acceptable condition.

From an engineering perspective, it is important to identify the most suitable sites for the construction of bridges. The fact that many villages in the study area were left totally isolated after the floods and torrents motivated the consideration of bridges not only as an aspect of flood control but also as a means to be prepared for the outcome of such events. Figure 11.11 shows a road cut by torrents in the Jeddah area and also a virtual scheme for a bridge to be constructed.

Thus a number of factors need to be considered in the selection of bridge sites, including the urban transport network. This type of precautionary measure was not illustrated on the map (Fig. 11.8) of medium-scale flood controls.

11.2.5 The "Infiltration Domains"

Torrential rain results in accumulations of water on several terrain surfaces forming water patches, as was the case in the study area. This was evident from the damage map (Fig. 8.3), which showed that large areas were covered by water and not merely those on watercourses. These localities will retain water for long periods of time, maybe even over a month, especially where the surfaces have a low-infiltration rate and where the evaporation process is slow in wet seasons.

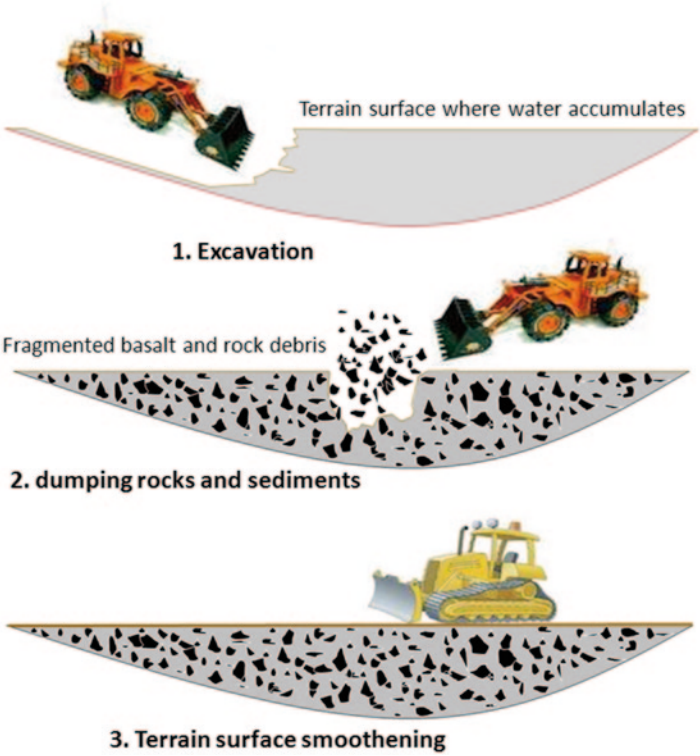


Fig. 11.12 Proposed system (Infiltration Domain) to avoid surface water accumulation and to infiltrate water in groundwater reservoirs

1. While this type of flood water does no remarkable damage to human beings, the following points can be made about it: Accumulated water must be removed so that transport and other human activities will not be affected
2. This water can be harvested rather than wasted.

This water gives rise to pollution and needs to be reduced because of its negative environmental impact. For these reasons, the current study gives attention to this aspect of flood water from the viewpoint of an integrated system of investment, whereby it will be used to replenish groundwater reservoirs. Since the terrains where this water accumulates are composed mainly of soil and mud (impermeable media), and in order to enhance the infiltration rate, the following steps are proposed (Fig. 11.12):

1. After drying out, these localities are excavated to the depth of a few meters.
2. Dumping rock masses of fragmented basalt, which is amply available in the surrounding regions, and rock debris and sediments into the excavated locality.
3. Smoothing the terrain surface using appropriate tools.

Taking these steps will create an intake locality that is suitable for use. Also, the flood water which has accumulated and resulted in the contamination of the environment on the terrain surface will infiltrate groundwater reservoirs. In addition, this system will stabilize the terrain materials, which are frequently drifted. Figure 11.8 shows typical sites for the proposed infiltration domains in the area of study.

11.3 Large-Scale Flood Controls

With regard to construction work in Jeddah aimed at reducing the impact of floods and torrents, both past and present projects have focused only on large-scale controls as a means to attain a perfect and sustainable solution. However, this is not a realistic approach, because if any of these controls fail, flood events may occur again. In addition, the structural frameworks of these controls, if unstable, present a threat to the inhabitants. This was clearly observed during the field survey of the area where these controls are established, such as at the Es-Samer and Omm El-Kheir dams. There, the inhabitants were more concerned about the rigidity of the dams rather than their utility in reducing flood impact. This does not apply, however, to small and medium-scale controls.

In the current study, there was an emphasis on the existing large-scale controls, and thus their setting was diagnosed after considering geomorphologic and hydrological concepts. This in turn leads to a consideration of appropriate solutions.

11.3.1 Widening the Old Channel and Constructing Basins

As observed in the previous chapters, the storm-water drainage “old channel” is an effective measure; in fact it is considered to be one of the best controls implemented to reduce the impact of floods and torrents in Jeddah and its surroundings. If the urban zones had not extended beyond this channel to the east, this channel would be continually effective. The old channel is still the major tool for dealing with floods and torrents in the region and this is why most of the works in progress are oriented toward joining the old channel with the newly established ones; the resultant route will in turn convey torrential water seaward.

It is essential to consider the geometric dimensions of different components of the newly established channels. This is because the dimensions of the old channel are not adequate to receive the loaded water bulk from the dams and from the convey channels that have recently been constructed. The construction of new open channels (i.e. convey channels) outside the urban areas is a correct implementation. However, conserving the old channel is also important, not only because it is part of the heritage of Jeddah City, but also because it can still play an integral role in draining torrential water to the sea if the cross-section of the channel is widened and if the joining with the new convey channels from the adjacent valleys is properly achieved.

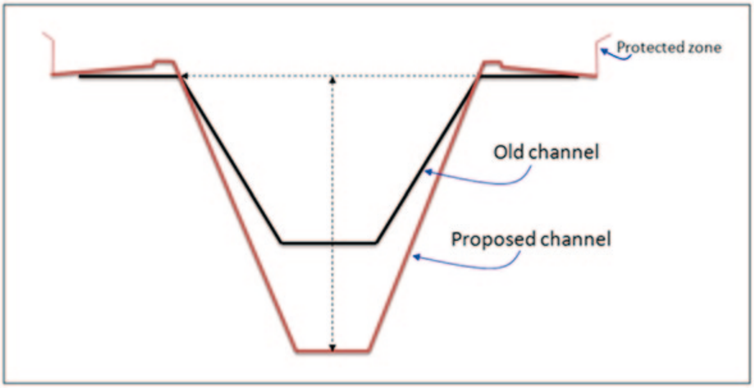


Fig. 11.13 Proposed widened cross-section of the old channel

According to available data, which includes the volume of rainwater, the level of flood water and bed load, the following guidelines were presented by the author (Al-Saud 2010c) with regard to the widening of the old channel:

1. In widening the old channel, the focus must be on the depth rather than on the width. The increase in depth should not be less than 1.5 times the existing depth, taking into account the symmetry of the section when the depth is increased.
2. Proper engineering practice must be followed to increase the slope gradient of the old channel to at least 10 m/km, which is low enough to transport water and withstand sedimentation processes.
3. The upper parts of the channel section must be modified according to the widened shape, as shown in Fig. 11.13, so as to be protected from the transported sediments.

The recent field survey of the Jeddah area showed that concerned sectors have committed to widening the old storm-water channel and that work has already begun. While there is some diversity in terms of engineering specifications, the applied approaches are very similar to those recommended by the author. Figure 11.14 shows how the old storm-water may be widened.

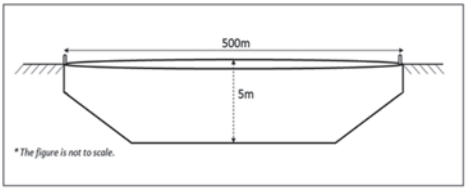
4. Ground water-storage basins must be constructed with a semi-conical scheme, a diameter of about 500 and 5 m depth (Fig. 11.15). These basins, which should be constructed at certain intervals along the old channel, will receive large water volumes from the running water in the old channels (Fig. 11.16), and this will decrease the water load in these channels.

It is suggested that two ground water-storage basins are constructed along the Northern channel and one each for the Middle and Southern channels (Fig. 11.17).

5. A protected zone must be created along the two flanks of the channels (Fig. 11.13).
6. The old channel (the storm-water drainage) must be cleaned and maintained on a regular basis.

Fig. 11.14 Implementations on widening the old storm-water channel in Jeddah

Fig. 11.15 Proposed cross section for a ground water-storage basin



11.3.2 Convey Channels and Crossing Canyons

The modifications of the storm-water channel and the related implementations proposed in the previous section were just the first stages in a project whereby water will be conveyed between valleys and the storm-water channel. The flow of torrential water from these valleys (i.e. east of Jeddah City) is characterized by non-uniform flow, and impacts with urban settlements in the sloping region. As mentioned previously, three types of convey channels have recently been executed and joined with the constructed dams.

However, the existing valleys in the study area are mainly wide and have several outlets in the downstream region, and due the undefined section of these valleys and their secondary tributaries it is not easy to join them with the convey channels. In order to solve this problematic issue, it is proposed that crossing canyons

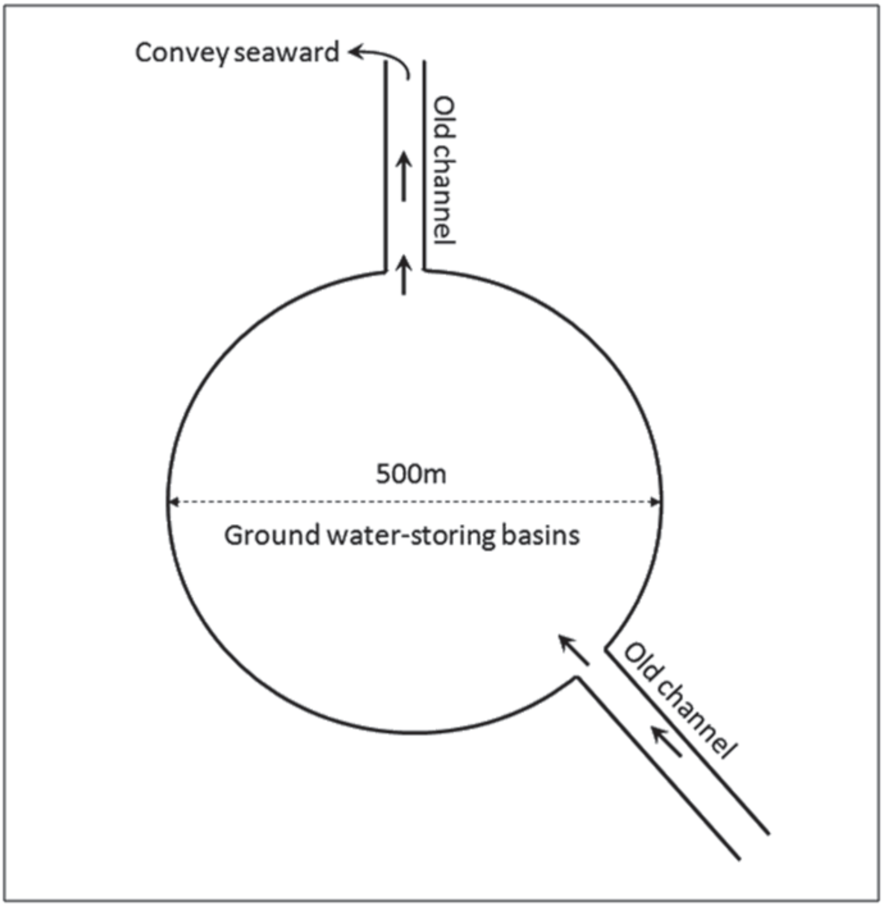


Fig. 11.16 Proposed scheme for a ground water-storage basin and its joining with the old storm-water channels

be established all over the width of the valley sections. This enables the capture of all water and sediment loads derived by the valleys and their secondary tributaries, thus facilitating their flow into the convey channels. In this approach, non-uniform flowing water will be collected in these canyons, and then drain from the canyons into the convey channels (Fig. 11.18).

The geometric dimensions of these canyons depend on the width of the valleys, soil and rock types and on the distance from the old storm-water channel. According to field observations, however, the depth of the canyons should range between 5–8 m and the width should exceed 20 m, and concrete materials should be used.

More than one convey channel can be joined with one valley, which can also be joined again with the old storm-water channel, as shown in Fig. 11.19. In this procedure, the slope gradient between the upper and lower points of the convey channels

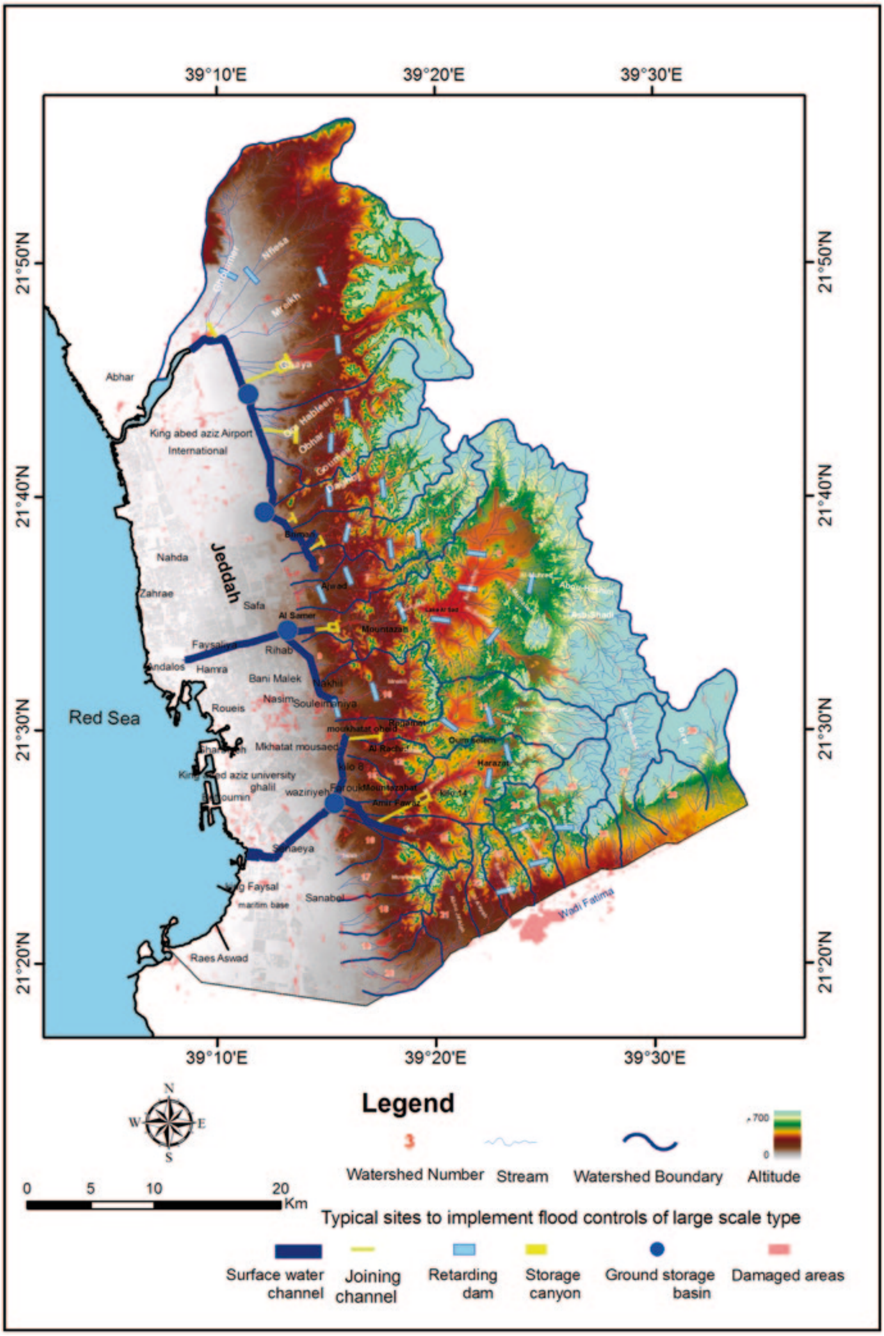


Fig. 11.17 Proposed typical sites to implement large-scale controls for floods and torrents in Jeddah area

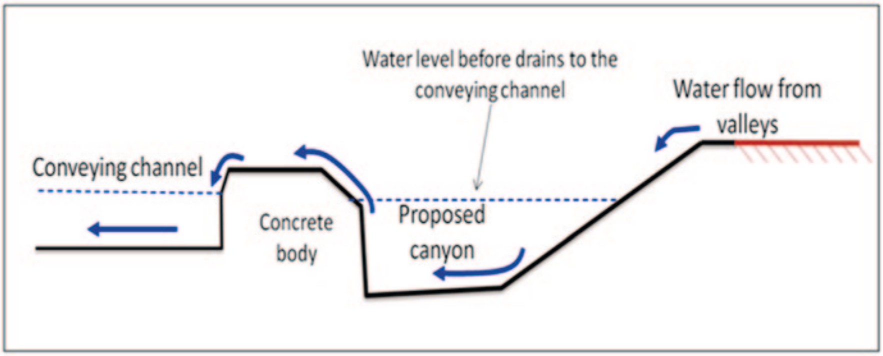


Fig. 11.18 Proposed crossing canyon and the related convey channels

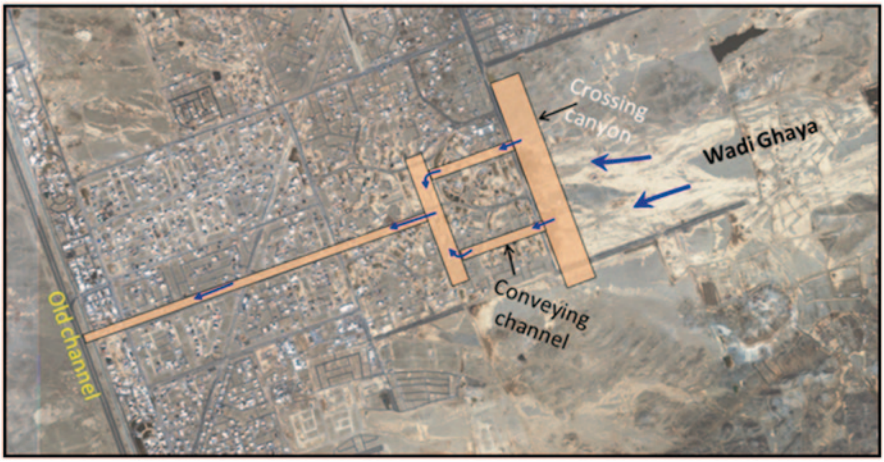


Fig. 11.19 Satellite image showing a proposed scheme for the crossing canyons and the convey channels along Wadi Ghaya

should be taken into account. Figure 11.12 shows typical examples of crossing canyons and convey channels in the study area.

11.3.3 Retaining Dams

Chapter 10 contained a detailed discussion of the dams that have been or are being built in the area of study. We also cautioned that unfavorable events may affect these dams, and that any leakage or failure can result in severe problems for the urban settlements that are located very close by. The risk of this happening can be lessened by reducing the load of the running water and sediments that accumulate behind these dams and thus decreasing its bulk.

In this regard, the proposed ground water-storage basins and crossing canyons can act in retarding water flow and then obtaining the uniform release of these ground water bodies to reduce the overflow, non-uniform run-off and collapse of terrain materials which may lead to severe damage. In this regard, the proposed ground water-storage basins and crossing canyons can act in retarding water flow and then obtaining the uniform release of these ground water bodies to reduce the overflow, non-uniform run-off and collapse of terrain materials which may lead to severe damages.

This study has also advanced another procedure whereby water flow energy can be retarded. This is the construction of a number of dams along valley courses. If another dam is built alongside the one at Wadi Kawes, for example, this will reduce the flow energy of water at the existing dam, and water energy will be distributed between the two dams instead of being concentrated on one. The construction of upstream dams on different scales means that they can act as crossing dams. Even on a small-scale, these "Retaining Dams" will decrease the impact of floods and torrents on neighboring urban areas during periods of torrential rain.

Figure 11.17 shows typical sites for the retaining dams that are proposed in the area of study. The number and dimensions of these dams is dependent on the decision of execution taken by the concerned governmental sectors, as well as on the geomorphologic and hydrologic characteristics of the valleys. However, it can also be a matter of managing costs and interests. In other words, the number of concrete dams can be reduced, if the number of rocky dams is increased. Also, the rocky dams can be executed along the secondary tributaries whenever it is necessary.

11.3.4 Integrated Plan to Support Sandy Flood Plains

Vast areas covered by sands and sediments are commonly observed on colored satellite images of the area of study. These are well pronounced on the eastern side of Jeddah city, and more specifically in the mountainous regions. No doubt, these sands and sediments will be shifted by the water that runs through the valleys during torrential rainfall. This is exactly what happened in November 2009 and January 2011, when the running water that reached the streets of Jeddah was full of sediments due to the high erosion rate that occurred then. This has been discussed in detail in the author's previous studies (Al-Saud 2010a, b, c). In these studies, the volume of transported sediments was estimated at 124 million m^3, which is a result of the terrain materials that eroded in the floods of November 2009.

The stabilization of the terrain surface was previously discussed in the section on small and medium-scale flood controls. However, this type of control must be considered within a framework of integrated plans to stabilize the valleys' flood plains that are characterized by thick sequences of sand and sediments. Stabilizing the terrain will reduce the erosion rate and the subsequent amount of impact. The proposed plan recommends the construction of cement retaining walls with a height exceeding 2 m and a length of several kilometers (Fig. 11.20). Cement blockage can also be applied to some territories where thick sands exist.

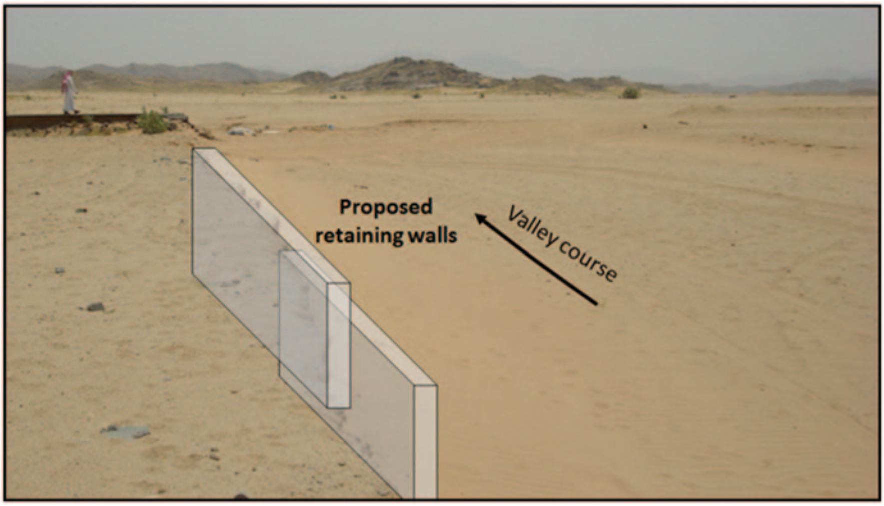


Fig. 11.20 Proposed cement retaining wall along valleys flood plains

11.3.5 Execution of the Proposed Infrastructure Works

It was clear from the map of the damaged areas (Fig. 8.3) that the largest amount of flood water was dissipated in patches, and that these were concentrated mainly in the urban zone along the coast. The major component of this water was direct rainfall, while the rest was derived from the neighboring valleys. This indicates that water will accumulate in urban areas, notably in the low-level lands and depressions, if proper drainage systems are not present. In this case, the mechanism of flood water in the coastal zone can be distinguished from that derived from the mountainous regions.

A successful approach to the issue of water accumulation would be if an integrated infrastructure project was applied in the coastal zone. This is exactly what was proposed by the Secretariat of Jeddah City, as described in the "Rapid Solutions" section in Chap. 10. While this will not reduce the impact of floods, which is principally originated in the mountainous areas, this is no reason not to carry out such a project.

11.4 Logistic Flood Controls

Supposing that all the above mentioned flood and torrent controls (with different scales) are applied in the area of study, however, a complete and integrated solution is still lacking. The current environmental problems are cumulative, moving from local to large-scale, and becoming more and more difficult to treat. In addition, nature is gradually changing, which means that these problems are being exacerbated by human interference. Therefore, the management of floods will never be perfect unless human behavior is governed by environmental concerns.

It has been clearly observed in many regions worldwide that the success of any project to conserve or improve the environment depends primarily on the behavior of the individuals living in those regions. Therefore, it is necessary to support technical flood controls with logistic controls derived mainly from legislation and laws that can be endorsed through workshops, meetings and symposia between stakeholders, experts, lawyers and the whole spectrum of concerned people. This can be summarized in the following items:

1. Presence of laws to prevent the chaotic encroachment of urban settlements on valley courses, even at remote distances.
2. Removal of the existing constructions located on valley courses.
3. Obliging the construction companies to conform to international standards with regard to all natural hazard mitigation processes, not only those related to floods and torrents.
4. Creating protection zones all along the old channel systems.
5. Preventing sediments dumping and the creation of landfills unless they are part of a creditable scientific study.
6. Conserving the environmentally-friendly measures in the area, notably those concerning responsible waste disposal at specified localities.
7. Obliging land owners in the wet and unstable lands to take part in plantation projects; this can be also supported by the relevant governmental sectors.
8. Creating laws according to which a technical report, which has considered environmental aspects, is required prior to the construction of urban settlements.
9. Removal of potentially dangerous installations and industries, such as power lines, oil refineries, etc., in the localities which have recently witnessed severe damages.
10. Punishing individuals and companies responsible for work that has ignored rules and regulations.
11. Setting up local campaigns and workshops to increase the inhabitants' awareness of natural hazards and to identify protective and preventative measures. Schools, households and other social institutions should all be included.

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Chapter 12
Discussion and Conclusion

Abstract This study has presented a new application of space technology in combination with the geo-information system. It has resulted in a number of new findings on the mechanism of floods and torrents that occur in Jeddah and the surrounding area. Thus, maps of flood-prone areas were obtained and appropriate flood controls were proposed. It is hoped that the study will provide useful information for the consideration of decision makers, experts, stakeholders and even the inhabitants themselves to better understand the natural and anthropogenic aspects which act on the occurrence of floods and torrents. It is recommended that similar studies be applied to many other regions of the Kingdom of Saudi Arabia.

A controversy still exists about the nature of the relationship between mankind and natural hazards, specifically the role that human intervention plays in their occurrence in relation to natural processes. No doubt, there are several issues to be considered in this matter and as we have seen from meetings and international conferences, there is growing debate in decision making in regard to most environmental issues; indeed, each state seems to hold different opinions. The latest topic to be raised is climate change, and there is a distinct lack of unified vision about it. It is well known that humans play a fundamental role in many aspects of natural hazards, particularly in the risk of floods and torrents that result in landslides, eroded rocks and soil, etc; although there are other types of natural hazards, such as earthquakes, where humans do not have any involvement. There seems to be a tendency to avoid the problem of climate change and pass the responsibility for dealing with it on to others. Yet it is essential that human beings do not activate or exacerbate the natural processes that may set the scene for catastrophes, as well as that they work toward better disaster management in order to mitigate the negative impact of these events.

Rarely a year goes by without the occurrence of disastrous floods in some part of the world, but there is a clear difference in the resulted damages between these parts. This is attributed to whether or not precautionary measures have been applied, whether and what flood controls have been implemented, and how they have been managed. The geomorphologic patterns and complex geological structures that exist in Saudi Arabia characterize it as an area prone to a miscellany of natural hazards. The entire region of the Arabian Peninsula encompasses many aspects of natural processes that give rise to natural hazards, which in turn have a negative impact on both humans and the environment.

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After more than thirty-five years, the flood issue has come back to the forefront and floods are top of the list of the natural hazards that exist in several regions of the Saudi Kingdom. Considering the occurred flood and torrent disasters, the resulting damages must be accorded to the magnitude of the natural processes themselves, and might have been smaller if precautionary measures and flood controls had been implemented. In the study area severe damages resulted from the magnitude of the flood processes and water distribution on the terrain surface. This implies that other forms of natural hazards may occur for which precautionary and protective measures are needed. The impact of the floods and torrents of 2009 was large and struck fear in the inhabitants. In 2011, another flood event struck the area north of Jeddah City and extended to some parts of the southern region, but it was less harmful to humans. However, the controls that should be implemented remained a matter of dispute. The consequence is that the inhabitants remain in constant fear that another such disaster may occur at any time. Looking at this phenomenon from another perspective, we can say that the city of Jeddah would be a safe natural setting, in particular in relation to floods and torrents, if human interference and chaotically structured urbanization had not taken place, in which case the floods and torrents would not have had the negative and severe impact that they have had in the past few years.

Natural processes such as the uniform flow of surface water along different watercourses take place regularly over the course of time. This should be the normal state of things in the study area, and thus the flow of water from the mountain regions along valleys should directly reach the sea. However, it is clear that the presence of dense urban settlements, such as the city of Jeddah itself and the surrounding areas impedes water flow or causes it to collide with residential neighborhoods and various urban facilities.

This is evident from the flood risk map that was produced in this study, in which the area was viewed in its natural state, as it would be without urban expansion. It shows that water was largely distributed through the natural watercourses in the valleys, and also that it accumulated in low-land areas. This map covers an area of about 264.2 km^2, which is equivalent to about 13.56 % of the study area. But the damaged zones that are identified through the analysis of satellite images of the area were distributed only in an area of about 140.56 km^2, which is approximately half the size of the areas at natural risk (i.e. 264.2 km^2). This is not due to preventive measures in the region, but to the existed collision between run-off water and residential areas, which reduced the geographic extent of flooded patches. The difference between the areas that are naturally prone to floods and the areas that were affected in 2009 and 2011 is reflected in the severe levels of damage.

After the flood event of November 2009, the immediate concerns of the inhabitants were rescue and reclamation, after which they sought to identify those who were supposed to be responsible for the management of natural disasters in the region; they were also concerned to discover the reasons for the occurrence. This led to various debates and disputes among different sectors and stakeholders as to what should be done. Was it possible that we had entered a new phase of natural disasters?

Following consultation between relevant governmental sectors, the necessary steps were implemented under the direct guidance of the Custodian of the Holy Mosques, Abdullah Bin Abdalaziz (*May God Save Him*). His Excellency issued a number of instructions with regard to immediate reclamation and the reformation of a stable environment, and ordered that new and appropriate projects be undertaken to reduce the impact of floods and torrents as soon as possible. These instructions were quickly followed, especially those regarding reclamation and rehabilitation work in the damaged zones. We believe that between the time of the first disaster in 2009 and the second disaster in 2011, some concrete actions were taken on the ground. Perhaps the disaster of 2011 served as a reminder of the need to take this issue seriously; especially since the lives and property of the citizens were left in a crucial condition.

However, these reclamation works began before any comprehensive and creditable study on the subject matter (except for some reports) became available. It really was a mandatory prerequisite to provide a comprehensive study on disaster management with a special focus on floods and torrents in the city of Jeddah and its surroundings. It was also necessary that this study included several data analyses and interpretations, and followed International Standards for proper application. Also, the engineering practices and the subsequent works should consider geomorphologic and hydrological concepts rather than focusing on the engineering structures and design aspects individually.

Perhaps mistakes still exist in determining the components of the problem. This would seem to be indicated by that fact that a series of dams were constructed in the region adjacent to the urban zones, and also the fact that many controls were implemented on the slopes and in the coastal region, when they should have been applied at the source of risk which is mainly in the high mountainous areas. Also, erroneous decisions were frequently made in the areas concerned. For example, the planned Briman zone intersects the course of Wadi Al-Hatil at several sites where no draining channels exist through the valley. Perhaps there are many questions still left to be answered about many subjects in the area of concern. In which case, is there any guarantee that in the event of heavy torrential rainfall such as in 2009 and 2011, the same harmful impact will not occur again.

There is still an urgent need to clarify the flood and torrent situation in the region from the viewpoint of proper environmental bases. There is also a lack of unified vision on this topic. In the light of this, there has recently been a series of studies on floods and torrents. These studies have dealt mainly with different aspects of analysis, including the technical aspects. This might substitute for the lack of earlier studies which should have served as advance preparation for floods and torrents; especially for an area like the city of Jeddah that was subject to two natural disasters the like of which had not been seen in decades and that is still at risk. In addition, there must be coordination between different institutions with regard to scientific research on natural hazards, and more specifically on floods and torrents and the relevant technical controls. This will play a substantial role in the integration of different concepts and the exchange of experiences and different techniques and methodologies.

This study was undertaken to clarify the problem and solutions to it, in terms of the information required in order to propose effective controls at different scales. It began by analyzing the effect of the natural characteristics in the region and interpreting the effect of human intervention. This it was based largely on the analysis of data from different sources including satellite images and field surveys, supported by basic data and various thematic maps. It was very significant that the study was able to identify more than ten thousand sites, with different aspects and scales, which were covered by water in the area of Jeddah. These sites are still at flood risk if torrential rain reoccurs. According to the damaged localities, these were found to constitute about 7.5 % of Jeddah and its surroundings. Roughly speaking, this means that about 7.5 % of the population of the area is at risk from floods.

The study also rated the degree of risk in these localities. It then proposed what controls and standards are required; these consist of small, medium and large-scale measures.

The effectiveness of the application of these controls can be summarized as follows:

- The application of small-scale controls alone will reduce the size of the damage by as much as 25 % (or less).
- The application of medium-scale controls alone will reduce the size of the damage by about 50–75 %.
- The application of large-scale controls alone will also reduce the extent of damage by about 50–75 %.

No doubt, the implementation of half the number of all these controls will reduce the problem significantly.

Perhaps we still need to reach reliable descriptions of the numeric data and to apply absolute values, such as the case, for example, of percentages of the above controls. There is still a need for detailed, comprehensive studies on the subject matter. These require joint collaboration in order to produce coordinated plans with regard to the optimal flood measures to be implemented.

We hope that this study has highlighted all the important issues in relation to flood and torrent control, and that it will give rise to further detailed studies on the matter.

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