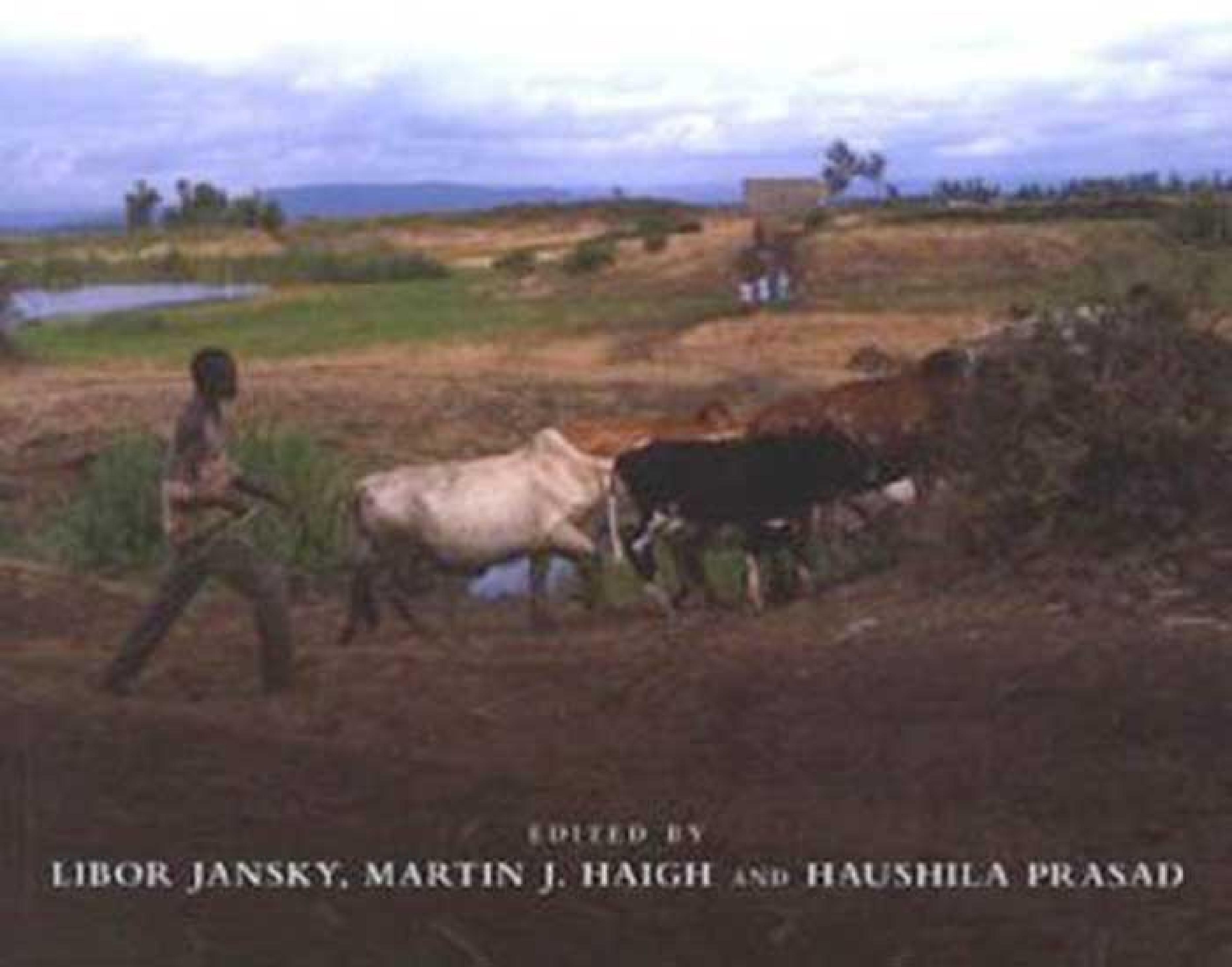
WATER RESOURCES MANAGEMENT AND POLICY

Sustainable Management of Headwater Resources

Research from Africa and India



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LIBOR JANSKY, MARTIN J. HAIGH AND HAUSHILA PRASAD

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Acknowledgements

In the path for attaining self-sufficiency and sustainability it is important to have the works of researchers, scientists, and policy-makers of developing countries, and those who have dedicated their lives to uplifting the poor, known to the external world. Though it was quite a big and ambitious move, we succeeded in getting most of the important stakeholders involved and this volume literally brings together their works from the fields of reality. The book basically derives from a conference on sustainable management of headwater resources held in Nairobi, Kenya, on 5–8 September 2002, which was jointly organized by the United Nations University, and Japan and United States International University (Nairobi, Kenya) in collaboration with Kenyatta University (Nairobi, Kenya), the International Association of Headwaters Control (IAHC), the International Association of Hydrological Sciences (IAHS), the World Association of Soil and Water Conservation (WASWC), the UN Centre for Human Settlements (UN-HABITAT), the UN Environment Programme (UNEP), and UNESCO.

As editors to this volume, we are primarily thankful to Remi Chandran, project assistant of the Environment and Sustainable Development Department of the United Nations University, for helping us throughout the long editorial process, and to Kumi Furyashiki, former programme associate, for her initial substantial contribution in bringing together the works of different authors.

We acknowledge the efforts of all authors who contacted us with regard to publishing their work; unfortunately, we had to be quite selective due to the large volume received, and only the best could be considered.

Editors

Preface

This book is a compilation of selected papers presented at the International Conference on Sustainable Management of Headwater Resources held in Nairobi, Kenya, on 5–8 September 2002. The major objective of the conference was to bring in case studies from the most fragile headwater areas in India and Africa and to focus on the major problems facing these regions. The Nairobi conference was also able to bring in researchers from various parts of the developing world and thereby give them an opportunity to share scientific and technical knowledge.

The book defines the concepts of headwater resources and later explains the engineering and technical aspects in sustainable management of various headwater resources in India and Africa. The introductory chapter by the editors explains the paradigms of sustainable management of headwater resources, policies, and prospects in various countries and finally the Headwater Declaration, which was one of the major outcomes of the conference.

The book also explains about local communities in the Nile interacting in developing sustainable management practices using indigenous knowledge of wetlands. Population growth, globalization, and state policies have threatened the headwaters of the Nile and have damaged their hydrological functions. It explains that indigenous knowledge must evolve in order to face the challenges of growing local and external pressures on wetlands, and indigenous knowledge within the wetland communities is mandatory for carrying out sustainable development practices in these areas.

A case study from the Bilate River delta of Lake Abaya in Ethiopia reveals the reasons for the increase in the water level for the past 10 years. It seems the water levels of Lake Abaya are increasing continuously even when the annual precipitation in the catchment is remaining constant. Analysis of lacustrine sediments of Lake Abaya showed high inputs of suspended loads and the reasons were attributed to high soil erosion in the catchment.

In Kenya, agricultural colonization of former government forests in the endorheic Lake Nakura basin has affected the balance of water resources surrounding that area, and this has been evaluated by analysing the rainfall, evaporation, river flow, and lake-level datasets. The studies revealed that there has been a decline in the lake levels and the cause was attributed to increased surface and subsurface abstractions for domestic and irrigation purposes. A catchment model of runoff and sediment yield for semi-arid areas has been also described, which is of significant importance in providing the tools for planning and resource management. This model has been able to simulate the dynamic interactions between vegetation and erosion by using the available soil moisture indices based on the assumption that water is the main limiting factor to plant productivity in a semi-arid catchment.

Sustainable management of headwater resources in the Indian subcontinent is also discussed in detail. Studies shows that the water resources of the Kumaon catchment in the Himalayas are diminishing due to reduced recharge of the groundwater in the area. The glaciers of the Greater and trans-Himalayas are also receding due to geo-hydrological disturbances, eventually leading to the drying up of springs.

A good description of the factors regulating fresh water quality in the Himalayan river system focusing mainly on two major rivers, the Brahmaputra and the Ganges, is also provided.

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Introduction

Sustainable management of headwater resources

Martin J. Haigh, Libor Jansky and Haushila Prasad

Introduction

Headwater regions provide the source for water resources and the margins of drainage basins, and they are the first- and zero-order basins that surround every catchment. The challenge is to define appropriate self-sustainable management strategies and structures for these lands which meet the needs of the headwater habitat, including its human inhabitants, and those of habitats downstream.

The finite and vital nature of fresh water as a natural resource has long raised concern regarding the socio-economic, political, and environmental security of human activities and ecosystem health in watersheds. Better fresh water resources management improves the welfare of poor people and reduces the risk of disasters such as floods, while improved water quality leads to better health and reduced child mortality. Almost 20 per cent of the world's population depend on poor water supplies to meet their daily needs, and many of such water resources are contaminated by disease-bearing organisms and other pollutants. Given the importance of integrated water resources management, the Millennium Development Goals – a set of time-bound and measurable goals and targets for combating various environmental and development problems adopted by heads of state at the UN Millennium Summit in September 2000 – include commitments to improve water security and ensure environmental sustainability (World Bank Group, 2003). Water management must also become a central component of the new educational and training programmes that will follow the launch of the UN Decade of Education for Sustainable Development, 2005–2014 (United Nations, 2003a). The hope is that this will encourage the world's people to reflect upon the consequences of their actions and focus more closely on the work of constructing more self-sustainable lifestyles (Tilbury and Goldstein, 2003: 1).

Headwater regions are defined as places where water flow-lines originate and where much groundwater recharge occurs. They are the ultimate source of a great portion of terrestrial fresh water. Technically, these lands are the zero- to first-order catchments on the margins of every river basin (Paracchini, Folving, and Bertolo, 2000). When water qualities and yields change in headwaters, the consequences affect the lands downstream.

Traditionally, headwater sources were associated with low levels of human occupation and isolation from major industrial and economic processes. Unfortunately, in the modern era many processes challenge the quantity and quality of water produced by headwater regions. Although located in the highest and most peripheral parts of a watershed, these regions lie at the front lines of human activities including agriculture, logging, mining, road construction, tourism, hydropower generation, and water supply. In some regions a booming economy is sponsoring economic growth and infrastructural developments that threaten biodiversity, unique habitats, valued landscapes, and minority cultures found in the watershed.

Among such development activities, conversion of forests into agricultural land in headwater regions is a major source of the problem of headwater degradation. Although improvements are being observed in some parts of the world today, as a whole it is estimated that the world has lost more than 900,000 square kilometres of forest in the past decade. Participants at the World Summit on Sustainable Development (WSSD), held in Johannesburg in September 2002, gave the highest new emphasis to sustainable mountain development over a quarter of a century, and so joined hands with the movement for sustainable management of headwater resources (United Nations, 2003b). Since many headwater regions are found in mountainous areas, while providing valuable fresh water supply to the ecosystems and human communities in the extended basins, discussions on better management of headwater regions have made valuable contributions to both the International Year of Mountains in 2002 and the following International Year of Freshwater in 2003.

Frameworks for Action on Water and Sanitation and Action on Agriculture

Arising with the WSSD, the WEHAB initiatives proposed by UN Secretary-General Kofi Annan aim to provide focus and impetus to action in five key areas: water, agriculture, biodiversity, energy, and health (United Nations, 2002). All of these frameworks impinge upon the sustainable management of headwater resources, especially the frameworks for Action on Water and Sanitation and Action on Agriculture. Headwater resources often lie on the margins of national and regional socio-economic systems, and some encompass political boundaries between rival social, cultural, and military groups. In such cases, economic and social marginalization of regional inhabitants may lead to emigration and the collapse of local environmental management and socio-economic systems.

In developing societies, many headwaters have suffered through colonization by peasant farmers who have been displaced from better-quality agricultural lands. Agricultural modernization has launched waves of economic migrants into the cultivation of unfamiliar and often unsuitable terrain. In such communities the struggle for immediate survival has higher priority than any concern for the future or the surrounding environment, even where the skills and resources needed for its management exist. In such cases, the problems of environmental degradation rarely remain in the headwaters. Regions downstream suffer through water and sediment pollution, changes in the hydrological regime, and reduced natural resource supply, which may also lead to social stress and livelihood disruption.

Today these regions face a variety of problems that affect not only the people residing in the headwater region, but also a greater portion of the population and ecosystems in the associated catchments. These include the provision of fresh and healthy waters and the problems of unsustainable agricultural production (Shisanya and Kwena, this volume; Subramanian, this volume). Many remote headwater regions are critical reserves of biodiversity (Rajwar, this volume) and sources of hydropower. Proper management of headwater resources has become one of the most significant modern challenges for environmental management and development.

Headwater Control Movement (HCM)

The HCM is a field-oriented grassroots movement that explores the role of environmental professionals in promoting the welfare of the environment and its inhabitants. It differs from most research networks in its attempts to link practitioners, researchers, and policy-makers from different backgrounds and disciplines in a common cause: the search for self-sustainable watershed management (Haigh and Krecek, 2000).

Headwater control is constructed on three principles.

- Headwater environments are threatened by environmental changes due to human action. HCM meetings routinely deal with problems caused by forest decline, land degradation, deteriorating water quality, and the damaging effects of air pollution, agriculture, road construction, tourist developments, and mining.
- Direct intervention can secure environmental quality. HCM meetings showcase many examples where pollution control, forestry, soil conservation, bioengineering, and/or community action have improved the vitality of the headwater environment.
- Solutions demand the practical application of coordinated and integrated environmental management. The HCM strives towards the integrated treatment of headwater landscapes – in both their biophysical and social components.

The aim remains to find an approach that unites the imperatives of environmental conservation, (self-)sustainable development, environmental reconstruction, the empowerment of headwater peoples, and the regeneration of livelihoods through policies and institutions that promote appropriate action.

Neglected thus far has been the role that could and should be played by environmental education for sustainable development, because over recent meetings it has become obvious that improved watershed management, like all environmental management, demands a change in social attitudes. This includes a shift in emphasis from granting primacy to short-term economic gains and away from belief in the still current myth that it is desirable for technology, routinely, to replace the functions of nature (Berry, 1999).

The practical disciplines of integrated watershed management involved in headwater control provide a unique collaborative environment for governmental and non-governmental organizations as well as international organizations (including some UN agencies) sharing similar goals.

The Nairobi conference was part of the Fifth International Conference on Headwater Control and it inherited some of the traditions and aspirations of its predecessors (Krecek *et al.*, 1989; Krecek, Rajwar, and Haigh, 1996; Haigh and Krecek, 1991, 2000; Krecek and Haigh, 1992; Singh and Haigh, 1995; Haigh *et al.*, 1998).

In 1989 the First International Conference on Headwater Control, held in Prague, Czech Republic, during that nation's "Velvet Revolution", marked the beginning of the Headwater Control Movement. The HCM focuses on improving the recognition and management of headwater-related environmental changes on the ground. The movement has sought, especially at the field scale, to promote better environmental understanding through empirical research, development of improved strategies for environmental reconstruction and conservation, and the design of better environmental management. The movement was initiated in the belief that if the headwaters of a region are in good condition, then they will transmit few problems downstream; since then, the HCM has been striving towards the integrated management of headwater landscapes in both their biophysical and social components.

Today, many headwater regions in the world share a variety of common problems, such as soil, forest, and water resource degradation, pollution by various external agencies, and poor management structures. Therefore, through the HCM, attempts have been made to exchange knowledge and experiences from different headwater regions in the world in order to attain better management. Like the United Nations University, the HCM has project aims to combine environmental and economic sustainability. Its researches deal with the key economic problems of the target region, be it steep-land agriculture in the tropics, reclamation of coal-mine land in Europe's headwaters, the management of fresh water in mountains or semi-arid regions, preserving water resource quality in the context of transboundary air pollution as in Central Europe, or restoration of the environmental and economic bases of rural communities in the war-torn Balkan states.

It was recognized that headwater management is often dominated by inappropriately defined institutional frameworks oriented to the extraction of particular resources for the benefit of outsiders. Frequently, this style of lopsided management also creates problems that are transmitted downstream, sometimes even to the same outsiders, through changes in the quality of water for their own use and population inflow from the headwater regions to urban areas. Teams of experts involved in the current project aim to help local communities take control of the management of their own environment and economic activities by promoting the development of community-based, environmentally informed, and holistic local management regimes (Van Haveren, 2000).

A key objective of headwater control is the ''uplift of all'', as stated in Gandhian principles. As mentioned above, the headwater management project aims at aiding local communities to build self-sustaining local systems for the management of their own livelihoods and environment, including biodiversity, natural resources, cultural icons, and the services their lands provide to outside communities and habitats.

Headwater control compared to other new movements in watershed management

Headwater control is one among several emerging ideologies that compete for the soul of watershed management. It contests a dominant mind-set that still sees watershed management in shallow and mechanistic terms, as a process where different technical experts isolate particular problems or resources for attention. Keidel (1996) aptly adapted the old parable of the four blind philosophers who describe an elephant by sending seven ‘‘visually challenged people’’ to evaluate a watershed. Individually, they decide that this land is perfect for nature conservation, for recreation, for water supply, agriculture, forestry, fishing, and mining – each finds that the land was ‘‘made’’ for their own favoured use beyond all others. These kinds of debates still dominate headwater management. Worse, current watershed management still aims to resolve problems either by constraining nature or by taking the functions of nature into human control. Its key concept is ‘‘sustainable development’’. However, today there exists a growing practical realization that the concept of sustainability is flawed. Sustainable, from its roots, means to hold up from below. Something is called sustainable if it is capable of being kept going through repair, maintenance, and management in ‘‘normal’’ conditions. Unfortunately, by extension, when such a system is not actively sustained, or when conditions are not ‘‘normal’’, it becomes liable to collapse and, meanwhile, its sustenance becomes a perpetual concern, cost, and responsibility. The alternative is to design for self-sustainability, creating systems that can look after themselves, either because their support is inherent in normal pattern of land use, or because environmental management is returned to the self-sustaining hand of nature. Headwater control strives for self-sustainability. The control systems which the HCM seeks to work with and within are nature and the local community, which the HCM would empower and engage in the self-regulation of their own habitats. In this respect, the movement epitomizes a shift in values across the applied environmental sciences.

Stern and Dietz (1994) recognize three current environmental value systems. ‘‘Egoistic’’ values predispose people to protect environmental attributes that affect them personally. ‘‘Altruistic’’ values subsume concern for the environment within the welfare of human society. ‘‘Biospheric’’ values grant primacy to all life, including that part which is human. Similarly, the ‘‘deep ecologist’’, Naess (1987), conceives the same egocentric, sociocentric, or anthropocentric and ecocentric or biocentric spectrum as a process of awakening, first to the personal self, then to the self defined as part of a human social group, and finally to the ecological self as part of the whole of living nature. Headwater control conceives the human component as an integral part of the watershed system, and that human welfare is best served by learning to live within nature and by serving the needs of nature.

Symptomatic of alternative thinking is the FAO's landscape-lifescape perspective, as developed in its electronic conference on land-water linkages in rural watersheds. This reflects a major functional, but ultimately unhelpful, division between those whose primary focus is the physical environment and the impact of its human intruders and those policy-makers whose concern is human welfare, which must be wrought against the opposition provided by the inconveniences of the physical landscape and, often, its inhabitants. The "lifescape perspective", called a defining characteristic of watershed management, is founded in the realization that since the benefits of environmental change are shared between the upstream and downstream shareholders in a watershed, so too should be the costs. Any development of policy, however, is forestalled by the workshop's wedding to the myth that many popular conceptions of upstream-downstream relationships, as well as the bases of "much land and water management policy", are inaccurate, uncertain, or "pseudoscience" (Togneti, 2000: 13). The workshop argues that there remains a need to take action on the best evidence available, whilst recognizing that this may be partial or incorrect (Togneti, 2000).

Superficially, the newly emergent applied systems science of "ecohydrology" fits the HCM vision. Ecohydrology purports to examine the tightly coupled interactions between water and life in order to enhance the sustainability of watershed management (Zalewski, Janauer, and Jolankaj, 1997: 13). It was conceived "to accelerate the transition from descriptive ecology, restrictive conservation and over-engineered management of aquatic ecosystems to analytical/functional ecology, creative management and conservation of fresh waters" (Zalewski, Janauer, and Jolankaj, 1997). In practice, ecohydrology differs from headwater control in its academic aspect and its emphasis on water quality and aquatic ecology. One recent typical paper, styled "Ecohydrology: Rediscovering freshwater ecology" (Gopal and Chauhan, 2001), may capture an ethos that focuses on nature but sees humans as external to the system. There are many chapters in this volume that could equally be labelled "Ecohydrology", but headwater control sees human welfare as a central concern.

Closer to the aspirations of the HCM are the various movements for sustainable agriculture, not least the "better land husbandry" (BLH) approach, which has been constructed through field projects in Kenya's Kakamega region and elsewhere in Africa (Hudson and Cheatle, 1993). BLH has grown from recognition that a large proportion of the money invested in conventional technical soil and water conservation (SWC) has been wasted. Structures constructed have not been maintained and land management recommendations introduced to local communities have not been adopted or maintained (Shaxson, 1997). The problem was that these measures did not sufficiently address the personal needs of the farmer, for whom production is infinitely more important that soil erosion. BLH, therefore, has strived to promote systems of farming that meet both the socio-economic needs of the farmer and the needs of the soil. BLH shifts emphasis from the volume of soils lost to erosion and the mechanical protection of the soil to the quality of the soil in the fields and its organic development, and from the needs of the whole watershed to the livelihoods of those who manage that soil through their land-husbandry practices (Shaxson, 1996; Shaxson *et al.*, 1997; Bunch, 1982).

BLH is good headwater control, and it illustrates the way ahead though the changing of human attitudes from ‘‘control’’ to ‘‘accommodation’’ and ‘‘self-control’’ or Gandhi-style *swaraj*, where the long-term sustainability of the human habitat is identified with the health of the whole habitat. Institutional constraints are a major obstacle to effective headwater management, and new institutions which are local, flexible, and holistic are needed. Central to this development is the emerging concept of ‘‘basin citizenship’’ (Van Haveren, 2000), where citizenship involves both rights and duties, including stewardship for lands managed as a public trust.

It is understandable that a ‘‘declaration’’ is as strong as its implementation, and in this respect the Nairobi Headwater Declaration (Appendix 1) has made a good claim to proving itself as a potent influence on those who will work on the sustainable management of headwater resources in the future. Several outcomes are immediately evident.

First is the development of an international commission ‘‘to provide direction and continuity for headwater issues and to create an awareness of headwater concerns at governmental level’’, which is being developed by a team led by Haushila Prasad of Kenyatta University, Kenya, and colleagues at Banaras Hindu University, India.

Second is the aim to pay ‘‘greater attention ... to applied environmental education aimed at building capacity for headwater management and changing social attitudes against wasteful and polluting uses of headwater resources’’. A team led by Martin Haigh prepared a special session on education for sustainable development at the Annual Conference of the Royal Geographical Society, London, September 2003, and was contracted to do the same at the International Geographical Congress in Glasgow, August 2004. This work has generated two special theme issues of the *Journal of Geography in Higher Education*, which has been ranked in the top dozen or so international journals for both geography and education, to be released near the start of the UN Decade of Education for Sustainable Development (United Nations, 2003a; Higgitt, Haigh, and Chalkley, 2005).

Third concerns the advice that "greater attention needs to be paid to the special roles and hydrological functions of headwater wetlands and peat lands, which should be a special focus for future headwater workshops". Under the leadership of Josef Krecek, the International Association for Headwater Control hosted a special NATO Advanced Research Workshop on the Environmental Role of Wetlands in Headwaters, which was held in Mariansky Lazne, Czech Republic, in December 2003 (Krecek and Haigh, 2005).

Fourth, and most important, builds on the advice that "UN agencies should continue their work with all stakeholders to appraise their situations, to identify gaps in knowledge, needs and constraints, and to support them in their efforts to resolve their problems and undertake practical action towards more self-sustaining and environmentally sensitive development" and on the headwater movement's concern for peace and environmental reconstruction in the new Balkan states. Under the leadership of Professors Miodrag Zlatic, Stanimir Kostadinov, and Nadia Dragovic, the World Association for Soil and Water Conservation (WASWC) launched a workshop on the natural and socio-economic effects of erosion control in mountainous regions at Belgrade University, Yugoslavia, in December 2002 (Zlatic, Kostadinov, and Dragovic, 2003). This sought to reconstruct pre-war patterns of cooperation amongst the watershed managers of the Balkan states and set up an international working party. The WASWC working party reconvened under the wing of Professor Georgi Gergov in Sofia, Bulgaria, in July 2003, and in the presence of potential donors, including the United Nations University, launched a series of projects that included the creation of a Balkan database for the World Overview of Conservation Approaches and Technologies (WOCAT), a group to share experience of the special problems of integrated watershed management in post-socialist economies fronted by Professor Ivan Blinkov of FYR Macedonia, and a practical project for the management of a major international watershed. Later the team added a fifth activity, which was to undertake a campaign for the creation of an international land reconstruction research reserve on the coal-mine-damaged lands of the Maritsa-Iztok basin, a project fronted by colleagues at the Poushkarov Institute of Soil Science and Agroecology, Sofia.

The challenge for the future will be to ensure that these initiatives produce both positive and practical results. Meanwhile the HCM rolls onwards towards its Sixth International Conference at Bergen, Norway, in 2005, under the guidance of Einar Beheim. This meeting will address between five and seven key themes. Those agreed are conserving soil and water quality in headwaters (WASWC); interactions between forests and environmental quality in headwater catchments and lakes (IAHC); space research and GIS techniques for identification and classification of headwater catchments; holistic watershed planning in headwater areas; and assessment of environmental impacts in headwaters. Two further themes are contending for attention, and candidates include the Balkan states projects and education for sustainable development.

Conclusion – Key issues for the future

The Nairobi Conference on the Sustainable Management of Headwater Resources was conceived as a contribution to the International Year of Mountains and the International Year of Freshwater. Such concerns reflect two major themes of this and previous gatherings. However, the real context was the WSSD, the UN's World Summit on Sustainable Development in Johannesburg. Hopefully, this will build on the impetus for international environmental management that was initiated at UNCED in Rio in 1992. Of course, there are many questions about the ability of both government and intergovernmental agencies to deliver on the promises. Further, despite Rio, it is a fact that environmental decline continues at an alarming rate. However, Rio did begin to affect the way environmental policy is formulated and it is hoped that this will continue. As for this meeting in Nairobi, lost in Johannesburg, it is unlikely that the HCM could have made its voice heard. But Nairobi's larger status of being an independent "break-out conference" and the major support provided by the United Nations University and sister agencies may allow its outcome, the Nairobi Headwater Declaration, to have a greater impact.

Headwater control (the HCM) began as a federal conference of NGOs. NGOs stand for the belief that they can improve the world by "thinking globally and acting locally". More than a decade ago, at UNCED (Rio), the NGO Forum produced a set of alternate treaties, which also set out a prospectus for the NGOs. They worried about the "erosion of basic values and the alienation and non-participation of almost all individuals in the building of their own future" (UNCED NGO Forum, 1993: 5.4). They recognized "the central role of education in shaping values and social action". This education would include developing "an ethical awareness" and "a respect for all life cycles", and it would self-impose "limits on humans' exploitation of other forms of life" (UNCED NGO Forum, 1993: 5.21). The human dimension of headwater management remains its major challenge. Let us hope that the Nairobi Headwater Declaration and these scientific proceedings can advance better and active self-management of headwaters by their human populations and a more self-sustaining integration of the human within nature.

Meanwhile, many questions remain to be answered, including the following.

- Are we sharing lessons learned locally in science and technology effectively?
- Are we engaging community participation properly?
- Is our technology really working?
- Are we really directing our research efforts to the most appropriate and necessary targets?
- Are our activities sustainable?
- Are our management structures appropriate?
- Do we have the best policies?

REFERENCES

Berry, T. M. 1999. *The Great Work.* New York: Bell Tower.

Bunch, R. 1982. *Two Ears of Corn: A Guide to People-Centered Agricultural Improvement*. Oklahoma City: World Neighbors.

Gopal, B. and M. Chauhan. 2001. "Ecohydrology: Rediscovering freshwater ecology", in V. Subramanian and A. L. Ramanathan (eds) *Ecohydrology*, UNESCO-IHP Series. New Delhi: Capital Publishing, pp. 339–354.

Haigh, M. J. and J. Krecek. 1991. "Headwater management: Problems and policies – Special feature", *Land Use Policy*, Vol. 8, pp. 191–205.

Haigh, M. J. and J. Krecek (eds). 2000. *Environmental Regeneration in Headwater Areas*, NATO Science Series 2: Environmental Security 68. Dordrecht: Kluwer.

Haigh, M. J., J. Krecek, G. S. Rajwar, and M. P. Kilmartin (eds). 1998. *Headwaters: Water Resources and Soil Conservation*. Rotterdam: Balkema.

Higgitt, D., M. J. Haigh, and B. Chalkley. 2005. "JGHE Symposium: The United Nations Decade of Education for Sustainable Development", *Journal of Geography in Higher Education*, Vol. 29, No. 1, pp. 9–92 and Vol. 29, No. 3 (in press).

Hudson, N. and R. J. Cheatle (eds). 1993. *Working with Farmers for Better Land Husbandry*. London: Intermediate Technology Publications/WASWC.

Keidel, J. 1996. "The blind people and the watershed", *Forestland Steward Newsletter (California Forest Stewardship Program)*, Fall, available at http://ceres.ca.gov/foreststeward/html/newsletter.html.

Krecek, J. and M. J. Haigh (eds). 1992. *Environmental Regeneration in Headwaters (Proceedings of the Second International Conference on Headwater Control)*. Prague: ENCO.

Krecek, J. and M. J. Haigh (eds). 2005. *Environmental Role of Headwater Wetlands.* Dordrecht: NATO/Kluwer.

Krecek, J., H. Grip, M. J. Haigh, and A. Hocevar (eds). 1989. *Headwater Control*. Pilsen: WASWC/IUFRO/CSVTS.

Krecek, J., G. S. Rajwar, and M. J. Haigh (eds). 1996. *Hydrological Problems and Environmental Management in Highlands and Headwaters*. Rotterdam: Balkema.

Naess, A. 1987. "Self-realization: An ecological approach to being in the world", *Trumpeter*, Vol. 4, No. 3, pp. 128–131, available at http://trumpeter.athabascau.ca/; reprinted in A. Drengson and Y. Inoue (eds). 1995. *The Deep Ecology Movement, An Introductory Anthology*. Berkeley, CA: North Atlantic Books.

Paracchini, M. L., S. Folving, and F. Bertolo. 2000. "Identification and classification of European headwaters", in M. J. Haigh and J. Krecek (eds) *Environmental Regeneration in Headwater Areas*, NATO Science Series 2: Environmental Security 68. Dordrecht: Kluwer, pp. 67–79.

Shaxson, T. F. 1996. "Principles of good land husbandry", *Enabl*e, Vol. 5, pp. 4–13.

Shaxson, T. F. 1997. "Soil erosion and land husbandry", *Land Husbandry*, Vol. 2, No. 1, pp. 1–14.

Shaxson, T. F., M. Tiffen, A. Wood, and C. Turton. 1997. "Better land husbandry: Rethinking approaches to land improvement and the conservation of water and soil", *Overseas Development Institute, Natural Resource Perspectives*, Vol. 19, available at www.odi.org.uk/nrp/19.html.

Singh, R. B. and M. J. Haigh (eds). 1995. *Sustainable Reconstruction of Highland and Headwater Regions*. New Delhi: Oxford University Press/IBH.

Stern, P. C. and T. Dietz. 1994. "The value basis of environmental concern", *Journal of Social Issues*, Vol. 50, pp. 55–84, available at www.findarticles.com.

Tilbury, D. and W. Goldstein. 2003. *Supporting the United Nations Decade on Education for Sustainable Development, 2005–2015.* Gland: International Union for the Conservation of Nature, Commission in Education and Communication, available at www.lut.mah.se/nms/forskarnatverk/ESDstatementdoc6.pdf; also www.iucn.org/cec/documents/ACF8B55.pdf.

Togneti, S. 2000. *Land Water Linkages in Rural Watersheds, Electronic Workshop, 18–27 September 2000, Synthesis Report*. Rome: FAO.

United Nations. 2002. *World Summit on Sustainable Development (WSSD) Wehab Framework Papers: A Framework for Action on Water and Sanitation*, United Nations, Johannesburg Summit 2002, available at www.johannesburgsummit.org/html/documents/summit_docs/wehab_papers/wehab_water_sanitation.pdf.

United Nations. 2003a. *Resolution 57/254. United Nations Decade of Education for Sustainable Development*, Resolution adopted by the UN General Assembly, 57th Session, 21 February 2003, Agenda Item 87(a) 02 55612, Document A/RES/57/254. New York: United Nations, available at www.unesco.ch/pdf/UNDekade.pdf.

United Nations. 2003b. *Johannesburg Summit 2002*, available at www.johannesburgsummit.org/.

UNCED NGO Forum. 1993. "Treaty on Environmental Education for Sustainable Societies and Global Responsibility", in R. Pollard (ed.) *The NGO Alternative Treaties From the Global Forum at Rio de Janeiro, June 1–15, 1992*, revised edition, available at www.igc.org/habitat/treaties/.

Van Haveren, B. P. 2000. "Reconstructing headwater areas: Social and institutional considerations", in M. J. Haigh and J. Krecek (eds) *Environmental Regeneration in Headwater Areas*, NATO Science Series 2: Environmental Security 68. Dordrecht: Kluwer, pp. 223–230.

World Bank Group. 2003. *Millennium Development Goals*, available at www.developmentgoals.org/Environment.htm.

Zalewski, M., G. A. Janauer, and G. Jolankaj. 1997. *Ecohydrology: A New Paradigm for the Sustainable Use of Aquatic Resources*, International Hydrological Programme V, Technical Documents in Hydrology 7. Paris: UNESCO.

Zlatic, M., S. Kostadinov, and N. Dragovic (eds). 2003. *Natural and Socio-Economic Effects of Erosion Control in Mountainous Regions, Proceedings.* Belgrade: Belgrade University Faculty of Forestry/WASWC.

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Part I

Studies on sustainable management of headwaters in India and Africa

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1

Issues and strategies for sustainable rangeland management in the headwaters of the Garhwal Himalaya

Govind S. Rajwar

Introduction

Rangelands are defined as "the areas of the world, which by reasons of physical limitations – low and erratic precipitation, rough topography, poor drainage, or cold temperatures – are unsuited for cultivation which are a source of forage for free ranging native and domestic animals as well as a source of wood products, water and wildlife" (Stodar, Smith, and Box, 1975). The term "range" implies broad, open, unfenced areas over which grazing animals roam. Rangelands include the meadows and pastures of alpine regions, grasslands of the temperate regions, and under the forest in temperate and tropical regions of the world.

The Himalaya, one of the youngest mountain systems of the world, are known for their beautiful landscapes, rich biodiversity, vast river system, snow-clad peaks, and varied topography and climatic conditions. The important sectors of the Himalaya from east to west are the Eastern, Central, and Western Himalayas. The Western Himalaya include the Uttaranchal, Himachal, and Kashmir Himalaya from east to west. The Uttaranchal Himalaya consist of two parts, the Garhwal and Kumaun Himalaya. In the Garhwal Himalaya the vegetation types range from tropical submontane to subalpine forest, alpine scrubs, and alpine meadows (Singh and Singh, 1992). In high altitudes of the Garhwal Himalaya rangeland covers large areas intermixed with forest vegetation, as in the present study area.

Three broad rangeland types have been identified for India by Puri *et al.* (1989). These are xerophilous grassland, mesophilous grassland, and hygrophilous grassland. In the Western Himalaya, Gupta and Nanda (1970) have distinguished 11 types of rangelands, which are grouped under alpine and subalpine, temperate, and subtropical and tropical grassland. Each of these types is further subdivided on the basis of dominant grass genera. In the alpine group the types are *Agrostis* type, *Danthonia* type, *Puccinella* type (confined to Kashmir), and *Phleum* type.

A proper understanding of the rangelands is complex because of the influence of biotic factors such as grazing, burning, and cutting on the whole tree-rangeland relationship. The changes in the intensity of these factors result in the formation of a large number of communities. Rangeland consists of plant communities with a mixture of grasses and other herbs. Rangelands may occur from sea level to an elevation of 5,000 m, but are best studied in the interior of great landmasses and plains (Polunin, 1960). They usually develop in areas with 25–75 cm of annual precipitation. Rangeland ecosystems occupy approximately 45 million km^2 of the world in tropical, temperate, and alpine regions, and have the highest cover (24 per cent of the total vegetation cover) of all the vegetation types (Shantz, 1954). India has 180,000 km^2 of rangeland, most of it in the Himalayan region.

In the Himalayan region, rangelands are important for the following reasons.

- Rangeland ecosystems are the most extensive ecosystems in the Himalaya, extending from the Siwalik foothills to lush alpine meadows and further extending to the trans-Himalaya (cold, arid zones of the Greater Himalaya) and Tibet.
- These ecosystems are unrivalled in terms of biodiversity in this region.
- These ecosystems constitute the headwater environment for the major river systems. The water from these rangelands is of increasing importance for generating hydropower energy and for agriculture based on irrigation at lower elevations.
- Rangelands provide habitats for numerous wildlife species, many of which are endangered, and for a wealth of plant species. Many plants are of medicinal importance and may provide important genetic material for future economic use.
- These ecosystems provide forage for livestock. Since cultivated agriculture is not possible on the rangelands, herding communities utilize animal products and unsuitable biomass themselves or sell them for income.
- These lands are gaining increasing popularity as tourist destinations, which can not only improve the livelihood of the local people, but can also be helpful in overall economic development.

Despite the importance of rangelands in the Himalayan region, these areas are poorly understood as scientific data on the ecological effects of grazing on the ecosystem and ecological processes are limited. The amount of biomass and dead organic matter gives a static picture of potential reserves of matter and energy that have been accumulated by the community over a certain time interval (Bazilevich and Rodin, 1971). According to Anderson (1971), the estimation of biomass is essential in determining the status and flux of biological material in an ecosystem. Primary production is an important parameter of rangelands. The ecological aspects of grazing and management of pastures have been emphasized by Stanford (1983) and Fleischner (1994).

Grazing is the process of complete or partial removal of the living or dead above-ground parts of herbaceous plants, and in grazing studies the interaction and interrelationships of the plant-animal interface are estimated (Heady and Childs, 1994). Studies on ecological aspects of grazing are based on the concept of co-evolution of pasture plants and herbivores (McNaughton, 1985; Heady and Childs, 1994; Behnke, Scoones, and Kervin, 1993).

India supports 1,118 million cattle, 1,072 million sheep, and 348 million goats. Grazing pressure in the Himalayan region of India is intense. It supports 20 million cattle, 10 million buffaloes, 3 million sheep, and 6 million goats. The cattle get their requirement of fodder mainly from forests and pastures. Pastoralism in the Himalaya is thousands of years old. In recent years many changes have taken place in this way of life due to developmental activities.

Range management is the science and art of optimizing the returns from rangelands for the benefit of society through the manipulation of range resources. Range management combines biological (vegetation ecology and animal-plant interaction), physical (climatic, topographic, and hydrologic factors affecting use of range resources), and social sciences (needs of the society based on range resources) (Bower, 1990). Conserving the rich biodiversity of rangelands is crucial for sustainable economic development, and grazing-related issues are the prime concern for the management of mountain protected areas. Pastoralists depend directly on plants, water, animals, and other natural resources of the rangelands for their livelihood (Pearson and Ison, 1987; Mohammad, 1989). The people residing on rangelands or in adjacent areas are also directly or indirectly dependent on rangeland resources. People-vegetation interaction, key species for conservation, and grazing policies make the bases for protected area networks (Rodgers and Panwar, 1988; Rodgers, 1989; Noss, 1994; Jina, 1995; West, 1996). Himalayan rangeland conservation plays a critical role in the overall economic development of the region and its people's well-being. Several Himalayan rangelands have been studied for biomass studies and grazing interactions in recent years (Dhaulakhandi, Rajwar, and Kumar, 2000; Mishra 2000). The present chapter evaluates the status of rangelands, grazing relationships, and issues concerning rangeland management in the buffer zone of Nanda Devi Biosphere Reserve in Chamoli Garhwal in the Himalayan region of Uttaranchal state in India.

Study area

The present study area is the buffer zone of the Nanda Devi Biosphere Reserve located in the Chamoli district of Garhwal region of Uttaranchal state in the Himalayan region of India. Parts of this biosphere reserve fall within Pithoragarh and Almora districts of Uttaranchal. The total area of the reserve is 2,237 km^2, consisting of an inner core zone (protected area) of 626 km^2 and an outer buffer zone of 1,611 km^2; it is situated between 79° 40′ E and 80° 5′ E longitude, and 30° 17′ N and 30° 41′ N latitude (Figure 1.1).

The north-eastern boundary of the reserve is formed by a tributary of the Girthi Ganga up to Untadhura peak, continuing up to Milam village in Pithoragarh district. The Gori Ganga forms the south-eastern boundary up to Martoli village in Pithoragarh and up to Khati village in Almora district along the Pindar River. The southern boundary is the Sundardhunga *gad* (a small river) along Khati village. The south-western boundary lies along the Samandar, Dhak, Mulkhet, Bartoli, Tribhuj, and Nanda Ghungti peaks. The north-western boundary is between Nanda Ghungti peak and Reni village in Chamoli district. The northern boundary is along the Dhauli Ganga River up to Malari village. The north-western area of the buffer zone is the present area of study. The study was conducted during the years 2000–2001.

Climate and soil

The reserve has generally dry climatic conditions with low annual precipitation, but heavy rainfall occurs during the monsoon (late June to August). The approximate variation in annual precipitation is from over 2,000 mm to less than 750 mm. The rainfall gradient decreases from south to north in Chamoli district, towards the north of Rishi valley. The upper Dhauli Ganga valley and Girthi Ganga valleys are dry. The entire area of the reserve gets snow in the winters in varying quantities. The higher reaches above 4,500 m elevation remain snow-covered all through the year. Summers are very short, lasting from mid-May to late August. The maximum temperature in the study area reaches 32°C in the month of July, whereas the minimum temperature goes below 0°C in the month of January.

The soils of the reserve are derived mainly from granite and metamor-

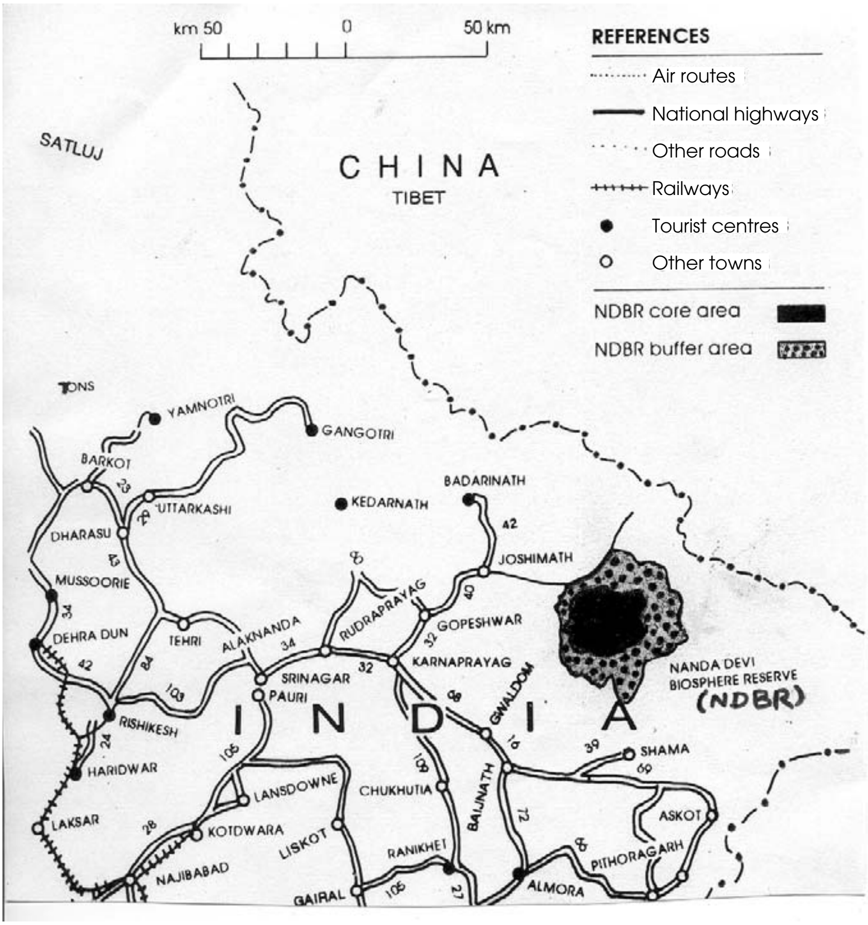

Figure 1.1 Study area

phic rocks. The texture of the soil in the north-western area is sandy with small proportions of silt and clay.

Methods

Livestock population

The livestock population was calculated for the six villages from information provided by the villagers and by observation of cattle of selected families (Figure 1.2).

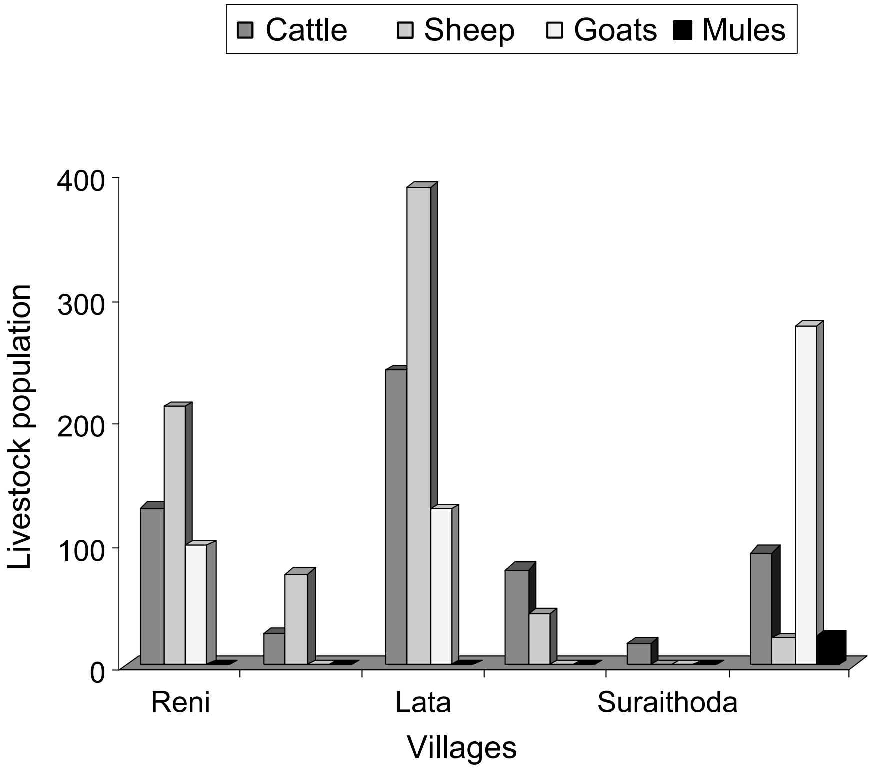

Figure 1.2 Proportion of livestock to villages

Cropping pattern and vegetation

The crops grown in the villages were noted in each season for the whole area. The vegetation study was based on sampling of plant species. The dominant plant species were noted for the pastures in the study area. The plants were identified with the help of the *Flora of Chamoli District* (Naithani, 1984/1985), and by reference to the herbaria of the Forest Research Institute (DD) and Botanical Survey of India (BSD) at Dehra Dun.

Above-ground biomass

Above-ground plant biomass was estimated by clipping the ground vegetation inside randomly placed quadrats. Ten quadrats of 20 cm by 20 cm size were selected for harvesting at monthly intervals. Above-ground plant parts were oven-dried and weighed to obtain the value of biomass.

Productivity was calculated by summing up the positive increments in biomass values following the method of Singh and Yadava (1974). Selected animals in each category were taken to the field for grazing and were allowed controlled grazing in a marked area.

Grazing behaviour

Grazing period

Total time spent by the animals in the field was noted. Besides this, time spent on resting, walking, and other activities during grazing was also recorded. Hours spent on grazing each day were calculated by following formula:

$$\begin{aligned}&\text{Hours spent on grazing/day}\\&\quad = \text{Grazing hours/day} - (\text{Time spent on walking}\\&\qquad + \text{Time spent on resting} + \text{Time spent on other activities})\end{aligned}$$

Bite frequency

The total number of bites taken by an animal in a 15-minute period was also recorded at different times during the whole day.

Bite size

To estimate the bite size two quadrats of one metre by one metre were placed in the field, and the animal was allowed to graze in one of them. Total number of bites taken in the quadrat were recorded. Both the plots were clipped, oven-dried, and weighed. Bite size was calculated by the following statement:

Weight of intact patch – Weight of grazed patch

Number of bites on the grazed patch

Bite size =

Consumption

For the estimation of consumption the following statement was used:

$$\begin{aligned}&\text{Consumption/animal/day}\\&\quad = \text{Bite size} \times \text{total bites during hours spent on grazing/day}\end{aligned}$$

Grazing period, bite frequency, bite size, and consumption of dry matter calculations are based on the method of Pandey (1981).

Table 1.1 Information about villages studied

Name of village	Resident/ migratory status	Altitude (m ASL)	Migrating distance (km)	Distance of summer settlements from road (km)
Reni	Sedentary	2,000	–	–
Muirana	Locally migrating	2,450	5	3
Lata	Locally migrating	2,415	2	–
Tolma	Locally migrating	2,800	5	3
Suraithoda	Sedentary	2,250	–	–
Dunagiri	Distantly migrating	3,600	More than 40	12

Results and discussion

Seasonal migration of population

Six villages located in the north-west region out of 12 villages in Chamoli district in the biosphere reserve were studied for livestock holdings, common cropping patterns, and the impacts of grazing (Table 1.1). The total population of these villages was about 800 and the number of families was about 160. Two villages were sedentary and their people remained inside the buffer zone of the Nanda Devi Biosphere Reserve throughout the year. However, many local people are semi-nomadic in lifestyle. Migratory villages are either locally migrating or distantly migrating. Three villages were locally migrating, meaning that their population migrates either within or "to and from" the buffer zone over a migrating distance of not more than 5 km. One village (Dunagiri) is distantly migrating, with a migrating distance of more than 40 km. Winter settlements are not far from the roads but summer settlements may be quite isolated. One of the most important changes noticed in these villages is that the number of occupied houses in the summer settlements is slowly decreasing every year because of the new lifestyles being adopted by the younger generation.

Cropping pattern

Agriculture with livestock herding and woollen cloth-weaving are the main occupations of the people. Different types of cash crops and traditional crops are grown in the study villages. Major cropping seasons are *Kharif* (March–August), *Jaid* (July–October), and *Rabi* (October–March). Crops grown in the villages studied are shown in Table 1.2, along with their sowing and harvesting months. The crops mature in four to five months. The crops grown in the high-altitude village of Dro-

Table 1.2 Crops grown in the area

Name of crop	Sowing to harvesting period
Cheena – hog millet or proso millet (*Panicum miliaceum*)	March–August
Oagal (*Fagopyrum esculentum*)	March–August
Phaphar (*Fagopyrum esculentum*)	March–August
Rajma – kidney bean (*Phaseolus* spp)	March–August
Black gram or *chana* (*Cicer arietinum*)	March–August
Potato or *alu* (*Solanum tuberosum*)	March–August
Finger millet or *koda* (*Eleusine coracana*)	May–September
Jhangora – ditch millet (*Papspalum scorbiculatum*)	May–September
Uwa – Himalayan barley (*Hordeum himalayense*)	May–October
Maize or *makki* (*Zea mays*)	May–October
Pea or *matar* (*Pisum sativum*)	June–September
Paddy or *dhan* (*Oryza sativa*)	June–September
Horse gram or *gahat* (*Dolichos biflorus*)	June–October
Amaranth or *chaulai* (*Amaranthus frumentaceous*)	July–November
Soyabean (*Glycine max*)	July–October
Wheat or *gehun* (*Triticum aestivum*)	October–March
Barley or *jau* (*Hordeum vulgare*)	October–March

nagiri include *uwa* (Himalayan barley), finger millet, *jhangora* (ditch millet), *cheena* (hog millet or proso millet), and *chaulai* (grain amaranth). Some cash crops are also grown in this village, and include potato, *rajma* (kidney bean), and amaranth. Other crops, except for cash crops, are grown in all other villages. Hay and straw of some crops constitute the fodder for livestock during the winter season.

There is only one village (Dunagiri) that keeps pack mules, presumably because the people of this village go on a longer migration. Suraithoda village has the lowest livestock holding and Lata village the greatest. In these study villages, the cattle population was approximately 32 per cent of the total livestock and sheep and goats were 67 per cent (Table 1.3).

Vegetation

The vegetation in the study area consists of forest, scrub, and rangeland vegetation. Open forest covers 42 per cent of the area of the reserve, which includes about 260 km^2 occupied by open forest and scrub. This forest includes the rangelands used by livestock for grazing. The common woody species in this area are *Abies pindorw*, *Betula utilis*, *Caragana gerardiana*, *Cedrus deodara*, *Juniperus communis*, *Pinus wallichiana*, *Quercus dilatata*, and *Rhododendron campanulatum*.

Table 1.3 Livestock population in the villages

Village	Cattle	Sheep	Goats	Mules	Total
Reni	128	210	97	–	435
Muirana	26	74	–	–	100
Lata	240	388	127	–	755
Tolma	78	42	–	–	120
Suraithoda	18	–	–	–	18
Dunagiri	92	22	275	24	413

Species diversity in the rangelands was highest in the month of October. Dunagiri pasture had more species diversity (32 varieties) than the Lata pasture (24). There are two growing seasons of herbaceous plants in the alpine zone: early-flowering and late-flowering plants. Early-flowering plants emerge soon after the melting of snow in early May and include *Ranunculus*, *Gentiana*, and *Primula* species, later followed by *Caltha palustris*, *Anemone rivularis*, and *Bergenia stracheyi* up to the beginning of June. Late-flowering plants emerge in June and flower up to mid-August, and include species of *Polygonum*, *Stellaria*, *Anaphalis* etc. (Rajwar, 1987). Maximum flowering occurs in the month of August. The plant communities in the rangelands of the study area were dominated by *Carex nubigera*, *Danthonia cachemyriana*, *Poa supina*, *Agrostis pilosula*, *Delphinium vestitum*, *Pimpinella diversifolia*, *Polygonum polystichum*, *P. affine*, *Rumex nepalense*, *Saxifraga androsacea*, *Swertias speciosa*, *Taraxascum officinale*, *Geum elatum*, *Anemone obtusifolia*, etc.

Above-ground plant biomass

The results of measurements of above-ground biomass of rangelands at four sites (two ungrazed and two grazed) are recorded in Table 1.4. The above-ground biomass increased from May to September on both ungrazed and grazed parts of Lata pasture and the ungrazed site of Dunagiri pasture, but it increased up to the month of August on the Dunagiri grazed pasture site. Maximum values of above-ground biomass were recorded in the month of September for both Lata pasture (756.7 g/m^2) and Dunagiri pasture (334.7 g/m^2) for ungrazed sites, whereas the minimum values were exhibited by grazed sites for the month of May (53.6 g/m^2) in the Lata site and for the month of October (24.5 g/m^2) in the Dunagiri site. Significant differences in the above-ground biomass between grazed and ungrazed sites were recorded in the months of September and October ($p < 0.05$) for Lata pasture, and in the month of October ($p < 0.05$) for Dunagiri pasture. In every month, the above-ground

Table 1.4 Above-ground plant biomass on grazed and ungrazed sites (sample n = 10)

	Above-ground biomass (g/m^2) ± SE			
	Lata pasture		Dunagiri pasture	
	Ungrazed site	Grazed site	Ungrazed site	Grazed site
May	82.0 ± 8.34	53.6 ± 5.28	68.4 ± 9.26	28.4 ± 7.63
June	218.5 ± 22.28	108.5 ± 6.72	186.3 ± 16.27	76.4 ± 16.83
July	468.6 ± 33.51	212.6 ± 14.63	255.5 ± 28.54	84.3 ± 15.53
August	522.4 ± 28.61	256.5 ± 25.2	286.3 ± 21.36	118.7 ± 21.82
September	756.7 ± 33.73	425.4 ± 37.18	334.7 ± 38.29	45.1 ± 16.43
October	458.2 ± 26.81	67.4 ± 26.45	108.2 ± 26.53	24.5 ± 8.29

biomass on the ungrazed site was >50 per cent greater than on the grazed site. However, the differences in grazed and ungrazed sites for other months were not statistically significant.

Comparing these results with those obtained elsewhere, average values of above-ground biomass in the pastures in the present study were higher than the values obtained for grazed and ungrazed sites of the Tungnath pasture in the Garwhal Himalaya (Sundriyal, 1992), but the values for ungrazed sites were near to the values of upper sites for a temperate forest rangeland in Uttarkashi, and higher for the Lata pasture and lower for the Dunagiri pasture in comparison to lower sites of temperate forest grazing land in Uttarkashi (Rajwar and Ramola, 1990). The results for the Lata pasture are comparable to the observations in an alpine grassland at Rudranath in Chamoli district made by Ram *et al.* (1988), whereas the above-ground biomass values observed in the Dunagiri pasture are near to the values obtained by Joshi, Raizada, and Srivastava (1988) in the Panwalikantha pasture at Tehri Garhwal.

Grazing pressure and impacts

The intensity of grazing pressure was maximum within 3 km distance from the village boundary. The frequency of cattle grazing was recorded on the basis of occurrence and density of dung piles, the signs of grazing, and the average grass cover. Beyond 3 km from the villages the grazing impact was low in the study area. However, despite suggestions that the number of cattle kept by the villagers is decreasing, the present livestock holding remains close to the rangeland carrying capacity.

Table 1.5 details certain parameters of grazing behaviour. The values are averages of data for the months of May to October. Maximum values

Table 1.5 Parameters of grazing behaviour of livestock in the study villages

	Grazer animal					
	Cow		Sheep		Goat	
Grazing behaviour (average value)	Lata pasture	Dunagiri pasture	Lata pasture	Dunagiri pasture	Lata pasture	Dunagiri pasture
Grazing period (hrs/day)	7.8	7.2	7.1	6.8	7.8	8.2
Bite frequency (hr^{-1})	632	645	780	730	583	566
Bite size (g/bite)	0.18	0.21	0.04	0.05	0.03	0.03
Dry matter consumption (kg/animal/day)	3.9	4.2	1.9	1.8	1.6	1.7

were obtained during September, followed by August, because of the maximum availability of forage during these months. The values of bite size and dry matter consumption were higher for the Dunagiri pasture than the Lata pasture.

These grazing values are comparable to those reported by Joshi, Raizada, and Srivastava (1988, 1991) for the Panwalikantha pasture, but higher than the values given by Negi, Rikhari, and Singh (1993) for a central Himalayan alpine pasture. The average foraging hours, bite frequency, and bite size were significantly correlated in different months ($p < 0.05$). The grazing pressure seemed to be not more than carrying capacity in these rangelands, except in the areas close to the villages where repeated grazing and overgrazing took place. The pressure of grazing in the areas close to the villages is due to the larger stock numbers and smaller distance travelled by them to these pastures. Some ecologists have suggested that the grazing pressure in most of the alpine meadows in the Himalaya does not exceed the carrying capacity (Singh, Singh, and Ram, 1988). Here, the cattle grazing pressure did not extend beyond 3 km from the village boundary in the study villages.

The greater mobility of goats enables them to be more selective in plant variety and habitat, in terms of both space and grazing time. Forage consumption is also greater for sheep than goats (Table 1.5). Grazing acts in two ways: by defoliation through eating, and by exerting physical damage through movement and through dung pats and urine etc. Grazing factors interact with each other and result in a syndrome, which needs to be broken down into individual factor effects (Arnold, 1987). One of the significant differences in the grazing behaviour of goats and sheep is that sheep bites are deeper, and therefore more harmful to the diversity of the rangeland species and their regeneration. Negi *et al.* (1993) found significant differences between the regrowth of different plant species in areas grazed by horses rather than sheep.

Livestock grazing affects the vegetation composition and structure of the rangelands, which was indicated by observations in the village surroundings where heavily grazed conditions have affected the species diversity, their structure, and their regeneration. The results of such studies are important in planning the management of rangelands. Due to unplanned grazing by higher numbers of livestock, the primary productivity of present pastures is likely to decrease. However, to determine the amount of the reduction requires a detailed understanding of the dynamics of the alpine rangeland ecosystems. Intensive grazing is correlated with a reduction in graminoid biomass, whereas it increases the sedge biomass (Mishra, 2001). Low to moderate grazing promotes species diversity and richness, which stabilize the ecosystems (McNaughton, 1967). Low and moderate grazing allow the exploitation of plant resources by a larger number of species, in contrast to resource use by fewer species at heavily grazed sites.

Strategies for management of rangelands

Conserving and managing biological diversity in the Himalayan rangelands are essential elements in the sustainable management and development of the region. The rangelands are highly resilient. Overgrazed ranges recover when they are protected from being grazed. Since rangelands provide forage for wild as well as domestic animals, their conservation is important to protect wildlife species. Habitat loss may affect the sustainability of the rangelands as well as reduce the forage habitats of different animal species. Protected area management plans have been developed with these objects in view. These are also essential to reduce human-wildlife conflicts.

The management of rangelands needs to take the scientific information available and synthesize it for practical management plans. One important concern for rangeland management is to control rangeland degradation through the regulation of livestock numbers. The responsibility of range managers is to maintain a balance between grazing pressure and the natural regeneration capacity of range plants. An evaluation of range condition is most important before formulating any plan for range management.

Since rangelands in the Himalayan region constitute the headwaters of major rivers, their conservation and management are necessary. The sustainable management of rangelands requires the following strategies to be adopted.

- Forage production and carrying capacity should be determined for all rangelands before finalizing any management plan. Analysis of ecological processes should be undertaken. Rangeland health should be considered an important parameter in management.
- Livestock grazing should be restricted to alpine pastures in higher altitudes and around village rangeland patches in the lower altitudes.
- Plant diversity should be monitored and maintained by managing the various grazing animals.
- Detailed investigation of forage potential should be used to determine the sustainable grazing pressure for pastures.
- The social conditions of the pastoralists and their problems should be considered in management plans.
- Measures should be implemented for reducing conflicts between livestock and wildlife.
- Alternative fodder resources should also be used when there is insufficient rangeland for sustainable grazing.
- Agricultural crop residues such as hay should be used to supplement range forage.

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REFERENCES

Anderson, F. 1971. ''Methods and preliminary results of estimation of biomass and primary production in a south Swedish mixed deciduous woodland'', in P. Duvigneaud (ed.) *Ecology and Conservation: Productivity of Forest Ecosystems*, Proceedings of Brussels Symposium 4, 1969. Paris: UNESCO, pp. 281–288.

Arnold, G. W. 1987. ''Grazing behaviour'', in R. W. Snydon (ed.) *Managed Grasslands. Analytical Studies (Ecosystems of the World 17 B)*. Amsterdam: Elsevier Science Publishers, pp. 129–136.

Bazilevich, N. I. and L. Y. Rodin. 1971. ''Geographical regularities in productivity and circulation of elements in earth's main vegetation types'', *Annals of Association of American Geographers*, Vol. 61, pp. 24–53.

Behnke, R., I. Scoones, and C. Kervin (eds). 1993. *Range Ecology at Disequilibrium: New Models of National Variability and Pastoral Adaptation in African Savannas*. London: ODI.

Bower, D. 1990. ''Range conservation and Sherpa livestock management in Khumbu, Nepal'', *Mountain Research & Development*, Vol. 10, pp. 34–42.

Dhaulakhandi, M., G. S. Rajwar, and P. Kumar. 2000. ‘‘Primary productivity and system transfer functions in an alpine grassland of western Garhwal Himalaya’’, *Tropical Ecology*, Vol. 41, pp. 99–101.

Fleischner, T. L. 1994. ‘‘Ecological uses of livestock grazing in western North America’’, *Conservation Biology*, Vol. 8, pp. 629–644.

Gupta, R. K. and P. C. Nanda. 1970. ‘‘Grassland types and their ecological succession in the Western Himalaya’’, in P. K. Gupta (ed), *Proceedings of XI International Grassland Congress*. Jhansi: Indian Grassland and Fodder Research Institute, pp. 10–13.

Heady, H. F. and R. D. Childs. 1994. *Rangeland Ecology and Management*. The Hague: W. Junk Publishers.

Jina, P. S. 1995. *High Pasturelands of Ladakh Himalaya*. New Delhi: Indus Publishing.

Joshi, S. P., A. Raizada, and M. M. Srivastava. 1988. ‘‘Net primary productivity of a high altitude grassland in Garhwal Himalaya’’, *Tropical Ecology*, Vol. 29, pp. 15–20.

Joshi, S. P., A. Raizada, and M. M. Srivastava. 1991. ‘‘Biomass and net primary productivity under a differed grazing pattern in a Himalayan high altitude grassland’’, *Range Management & Agroforestry*, Vol. 12, pp. 1–13.

McNaughton, S. J. 1967. ‘‘Relationship among functional properties of a California grassland’’, *Nature*, Vol. 216, pp. 168–169.

McNaughton, S. J. 1985. ‘‘Ecology of grazing ecosystem: The Serengeti’’, *Ecological Monographs*, Vol. 55, pp. 259–294.

Mishra, C. 2000. ‘‘Socio-economic transition and wildlife conservation in the Indian trans-Himalaya’’, *Journal of Bombay Natural History Society*, Vol. 97, pp. 25–32.

Mishra, C. 2001. ‘‘High altitude survival: Conflicts between pastoralism and wildlife in the trans-Himalaya’’, doctoral thesis, Wageningen University, The Netherlands.

Mohammad, N. 1989. *Rangeland Management in Pakistan*. Kathmandu: ICIMOD.

Naithani, B. D. 1984/1985. *Flora of Chamoli*, Vols. 1–2. Howrah: Botanical Survey of India.

Negi, G. C. S., H. C. Rikhari, and S. P. Singh. 1993. ‘‘Plant regrowth following selective horse and sheep grazing and clipping in an Indian Central Himalayan alpine meadow’’, *Arctic and Alpine Research*, Vol. 25, pp. 211–215.

Negi, G. C. S., H. C. Rikhari, J. Ram, and S. P. Singh. 1993. ‘‘Foraging niche characteristics of horses, sheep and goats in an alpine meadow of the Indian Central Himalaya’’, *Journal of Applied Ecology*, Vol. 30, pp. 383–394.

Noss, R. F. 1994. ‘‘Cows and conservation biology’’, *Conservation Biology*, Vol. 8, pp. 613–616.

Pandey, A. N. 1981. ‘‘Vegetation and bovine population interactions in the savanna grazing lands of Chandraprabha Sanctuary, Varanasi. II. Seasonal behaviour of grazing animals and an assessment of carrying capacity of the grazing lands’’, *Tropical Ecology*, Vol. 22, pp. 170–186.

Pearson, C. and R. Ison. 1987. *Agronomy of Grassland Systems*. Cambridge: Cambridge University Press.

Polunin, N. 1960. *Introduction to Plant Geography and Some Related Science.* New York: McGraw-Hill.

Puri, G. S., R. K. Gupta, V. M. Meher-Homji, and S. Puri. 1989. *Forest Ecology Volume 2. Plant Form, Diversity, Communities and Succession*. New Delhi: Oxford University Press IBH Publishing.

Rajwar, G. S. 1987. ''Vegetation types and floristic pattern in alpine zone of Garhwal Himalayas'', in Y. P. S. Pangtey and S. C. Joshi (eds) *Western Himalaya: Environment, Problems and Development*, Vol. 1. Nainital: Gyanodaya Prakashan, pp. 165–170.

Rajwar, G. S. and V. C. Ramola. 1990. ''Variations in net primary production of east and west facing slope montane grasslands of Uttarkashi, Garhwal Himalaya'', *Indian Forester*, Vol. 116, pp. 717–722.

Ram, J., S. P. Singh, and J. S. Singh. 1988. ''Community level phenology of grassland above tree-line in Central Himalaya''. *Arctic & Alpine Research*, Vol. 20, pp. 325–332.

Rodgers, W. A. 1989. ''Policy issues in wildlife conservation'', *Indian Journal of Public Administration*, Vol. 35, pp. 461–468.

Rodgers, W. A. and H. S. Panwar. 1988. *Planning a Protected Area Network in India, Vol. 1 – The Report*. Dehra Dun: Wildlife Institute of India.

Shantz, H. L. 1954. ''The place of grassland in the earth's cover of vegetation'', *Ecology*, Vol. 35, pp. 143–145.

Singh, J. S. and P. S. Yadava. 1974. ''Seasonal variation in composition, plant biomass and net primary productivity of a tropical grassland at Kurukshetra, India'', *Ecological Monographs*, Vol. 44, pp. 351–376.

Singh, J. S. and S. P. Singh. 1992. *Forests of Himalaya: Structure, Functioning and Impact of Man*. Nainital: Gyanodaya Prakashan.

Singh, J. S., S. P. Singh, and J. Ram. 1988. *Fodder and Fuelwood Resources of Central Himalaya: Problems and Solutions*, Report of Study Group on Fuel and Fodder Working Committee, Planning Commission. New Delhi: Government of India.

Stanford, S. 1983. *Management of Pastoral Development in the Third World*. London: ODI.

Stodar, L. A., A. D. Smith, and T. W. Box. 1975. *Range Management*. New York: McGraw-Hill.

Sundriyal, R. C. 1992. ''Structure, productivity and energy flow in an alpine grassland in the Garhwal Himalaya'', *Journal of Vegetation Science*, Vol. 6, pp. 15–20.

West, N. (ed.). 1996. *Rangelands in a Sustainable Biosphere: Proceedings of the Fifth International Rangeland Congress*. Denver, CO: Society for Range Management.

2

The role of sustainable wetland use in maintaining river flow: Some experiences from the headwaters of the Nile in Ethiopia and Rwanda

Adrian P. Wood

Introduction

Wetlands are small but significant areas in the headwaters of river systems. They provide critical water storage for sustaining the flow of streams and rivers within these areas and beyond. This chapter explores the problems faced in achieving sustainable wetland management in two countries in the Nile headwaters, Ethiopia and Rwanda. In these areas there is a need to balance the pressures to meet local needs whilst also maintaining the wider benefits from the hydrological functioning of these wetlands.

This chapter shows how local communities interact with wetlands and how they can develop sustainable management systems based on indigenous knowledge and technologies which produce a wide range of benefits. These sustainable use systems are under threat because of population growth, globalization, and state policies which are encouraging intensive drainage of these areas. As a result, many wetlands have become degraded, losing their hydrological functions and ability to provide products associated with an abundance of water.

This chapter suggests that if the environmental functions and local benefits of headwater wetlands are to be sustained, there is a need to develop a new approach to wetland management. This must avoid the state-dominated development policies, which look only at national production needs, and also overcome the predominant view of local agriculturalists. Instead a more holistic approach must be taken which recognizes the value of wetlands to a range of stakeholders, in both the headwater areas and downstream, and facilitates the development of sustainable wetland management through awareness-raising, local-level democratization, and the empowerment and support of indigenous institutions and knowledge systems.

The highland areas of Eastern and Central Africa fulfil an important regional role as the headwaters of the Nile. Indeed, these highlands can be seen as water-towers which sustain the flow of the Nile (Mountain Agenda, 1998). The critical way in which highland water sources affect river flow, and thereby extensive lowland areas, is a key reason for the increased attention given in recent years to upper-basin management in river systems around the world. To sustain the flow of the Nile, and ensure that the river has a favourable, rather than problematic, regime, attention must be given to land use in the headwater highlands, as well as to the various other elements of the hydrological system, such as barrages. This chapter reviews the role of one such land element, highland wetlands, in sustaining the flow of water from the highland catchments into the Nile. The review draws on a four-year study of the wetlands in the south-west highlands of Ethiopia, as well as recent investigations in Rwanda. From this experience, it is suggested that it is possible to achieve the sustainable multiple use of wetlands in order both to sustain the flow of the Nile and also to meet various local needs. It is also proposed that local knowledge and indigenous institutions have an important role to play in the coordination of wetland management to achieve this land-use pattern. In conclusion, a number of generic steps are identified which may be applied in headwater wetlands in order to help achieve sustainable forms of wetland management which will sustain the flow of rivers from the highland areas in Africa.

Wetlands in highlands – Their role, functions, and threats

The flow of water through, and out of, highland areas is determined by the interaction of rainfall, geology, land use, and interventions in the hydrological system, such as dams and diversions (Newson, 1994). The focus of this chapter is one aspect of the land-use system in highlands, wetlands, and the way in which the management of these areas affects the storage and release of water which sustains downstream flows. To date much attention has been given to the role of highland deforestation and poor land-use management in increasing the occurrence of rapid runoff events which induce more variable downstream flows, with increased flooding and low flows (Newson, 1992). However, as yet little attention has been given to the role of wetlands within highland areas, and the important role they play in storing water, regulating stream flow, and re-

Table 2.1 Wetland functions, products, and attributes

Functions	Products	Attributes
Water storage	Forest resources	Biological diversity
Groundwater recharge	Wildlife resources	Uniqueness to culture
Groundwater discharge	Fisheries	
Flood control	Forage resources	
Sediment retention	Agricultural resources	
Nutrient retention	Water supply	
Biomass export		
Micro-climate stabilization		
Water transport		
Recreation/tourism		

Source: Adapted from Dugan, 1990

ducing floodwater peaks (Maltby, 1986; Dugan, 1990; Amatya, Chescheir, and Skaggs, 1995). In this respect, wetlands can be regarded as the last natural resort in highland water storage and regulation once land degradation has reduced the infiltration and groundwater storage capacity of the interfluves.

Wetlands are of varying size in highland areas depending on the terrain. While in general they are of limited extent, in some parts of the world where highland plateaux are common, notably Eastern, Central, and Southern Africa, they are extensive, accounting for between 2 per cent and 12 per cent of the surface area above 1,000 m. Although generally small in size, highland wetlands are critical areas providing a number of important functions and products for the local communities and more widely. Table 2.1 provides a summary of the various functions which these wetlands can provide.

The key point to note is that wetlands provide a wide range of functions which help maintain the presence of water locally in highlands through groundwater recharge and storage, and that they regulate the flow of water from highland to lowland areas. This regulatory function reduces the temporal variability in downstream rivers and groundwater levels and, in effect, minimizes the occurrence of extreme hydrological events, such as flooding and low flow. In many parts of the developing world, the capacity of wetlands to act as "sponges" and maintain base flows during dry periods is critical to the livelihoods and subsistence of whole communities (Balek and Perry, 1973; Denny and Turyatunga, 1992; Grab and Morris, 1999).

The current situation is that highland wetlands are becoming subject to many of the same pressures which have already affected many lowland wetlands, and with the same results – the drainage of these areas for agricultural development and their subsequent degradation (Zimmerer, 1991; Million Alemayehu, 1996; Lema, 1996; Noble, 1996). However, the management of highland wetlands for agriculture is often more difficult, on account of the high rainfall, steep slopes, rapid runoff, and erosion associated with the terrain. Whilst drainage lowers the wetland water table, making crop cultivation possible, the destruction of natural wetland vegetation and the installation of a drainage network have the effect of rapidly transferring runoff through the wetland system, thereby reducing groundwater recharge and seriously restricting the wetland's regulatory and storage function. Often drainage leads to downcutting at the outlet of the wetland, erosion in the drainage channels, and a continuing fall in the wetland water table and storage. There is also usually desiccation and loss of wetland humus and soils, with compaction of the remaining soil. In the end, wetland degradation can mean that agriculture and other economically productive roles are greatly reduced as well. Whilst these changes have serious local implications for those using the wetland, other beneficiaries downstream, who rely on the storage and filtration functions of wetlands, are also affected by reduced supplies of water and poorer water quality.

The pressures leading to such changes in land use include population growth and the search for new agricultural land, technological innovation which facilitates water management and drainage, and commercialization forces as communications are developed and market access improves. As a result wetlands have become a new agricultural and commercial frontier in several parts of Africa, including the highlands in the eastern and central parts of the continent, and as such are subject to competitive claims with economically powerful groups appropriating these formerly common resources (Tegene Sishaw, 1998; Woodhouse, Bernstein, and Hulme, 2000). Further, as food security concerns and other development pressures grow, governments seek to ensure that the formerly remote headwater areas contribute to national development and may encourage wetland drainage for cultivation (Abbot and Afework Hailu, 2001). Even where such government pressures do not impact directly upon wetlands, but rather affect the watershed areas, there may be impacts upon wetlands because of stream-flow changes leading to wetland erosion. Particularly important is the impact of downcutting in highland wetlands due to increased peak flows, as this can very quickly lower the wetland water table and undermine the effectiveness of wetlands in hydrological stabilization.

In this dynamic situation a critical aspect is how these pressures and changes in land use are managed by communities and affected by government policies. Responses to this challenge should be informed by an understanding of the ecological dynamics of wetlands and the widespread implications of wetland change. However, for the most part wetlands are a neglected resource. Government agencies and many rural households who engage in wetland use find it difficult to see beyond the immediate and short-term results of wetland development. In particular, they often fail to recognize the longer-term degradation threats and the spatially more extensive impacts of these changes, which can be system-wide and transboundary in nature.

In some cases local knowledge of sustainable wetland management has developed through long periods of wetland use, often focusing on multiple-use regimes (Dixon, 2000; Howard, Bakema, and Wood, in press). In some cases this knowledge may be able to make an important contribution to the protection of wetlands and the maintenance of their hydrological functions (Adams, 1993; Hollis, Adams, and Aminu-Kano, 1993). However, such local knowledge tends to be focused on the products and locally beneficial functions of wetlands, rather than their wider contributions to the hydrological regulation of headwaters.

With these dynamics, it is clear that there is a need to improve understanding of how land-use management in headwater areas can ensure the survival of their wetlands in forms which at least will maintain their hydrological contribution for local and more distant beneficiaries and meet local needs for wetland products. The key question is how to make such land use economically attractive for communities and also environmentally sustainable. The suggestion in this chapter is that this process should build on local knowledge and local institutions, with elements of external support, and develop a process which ensures the participation of the full range of stakeholders. The Nile basin is a good example of where such improved headwater wetland management could contribute significantly to sustaining river flow, rather than distorting it.

The Ethiopian experience

Highland wetlands of south-west Ethiopia

The highlands of south-west Ethiopia consist of a dissected plateau with elevations ranging from 1,500 m to 2,300 m above sea level. The major rivers, the Abay (Blue Nile) to the north, the Didessa and Baro (Sobat) in the centre, and the Omo in the east, are all deeply incised into these highlands (Figure 2.1). The drainage of the area is primarily westward into the Nile system, although in the east and south drainage is into Lake Turkana. There are no major dams on these rivers as yet, although one hydropower dam is currently under construction on a tributary of the Omo and plans exist for a series of micro-dams, or barrages, for

Figure 2.1 The south-west highlands of Ethiopia

hydropower production in the headwaters of the Baro, building on the experience of the first such barrage near Metu on the River Sor, a tributary of the Baro (TAMS-ULG, 1996).

The annual rainfall in the south-west highlands varies from 1,200 mm in the east and extreme west to over 2,000 mm in the centre of the area. The single rainy season can be up to nine months in length (March to November), although the bulk of the rain is concentrated in the period from May to October (Tafesse Asres, 1996). The natural vegetation of most of the area is tropical montane rainforest, with bamboo forest at higher elevations and acacia savanna woodland in the more deeply incised valleys (Kumelachew Yeshitela, 1997). The montane forest has an understorey

Table 2.2 Land use in Illubabor zone, Ethiopia

	Land use (hectares)	Land use (% of total area)
Natural forest	384,973	23.1
Coffee	64,251	3.8
Cultivated and arable land	431,280	25.9
Plantation forest	5,037	3.2
Other perennial crops	17,440	0.3
Bush and grassland	421,101	25.3
Wetlands	22,677	1.4
Grazing land	178,108	10.7
Others	105,206	6.3
Total	1,630,073	100

Source: MoA, 1998

of wild coffee (*coffea arabica*) in many places, as well as a ground cover which includes spices such as Ethiopian cardamom (*Aframomum korarima*) (Table 2.2).

Much of the natural forest in this area was cleared by the mid-nineteenth century, but a population collapse following the conquest of this area in the last quarter of that century led to resurgence in secondary forest. This secondary forest has been subject to growing degradation since the mid-twentieth century, especially as road communications into the area have improved and as production of coffee, spices, and honey has been commercialized (Reusing, 1998). Nonetheless, the south-west highlands still contain the most extensive areas of highland forest remaining in Ethiopia today (Figure 2.1). Despite globalization, the bulk of the agricultural production in this area (excluding coffee) is for subsistence, with only a small percentage of production sold. Maize is the most important staple, with root crops more common in the wetter and more forested parts of the region. *Tef (Eragrostis tef)*, the staple of northern Ethiopia, has been introduced in some localities, but its small seeds, and the fine tilth which its cultivation requires, can lead to serious erosion (FAO, 1986).

Three major types of wetlands have been identified in the area: valley head, mid-valley, and the larger floodplain wetlands. In central Illubabor zone (see Figure 2.1), the valley-head wetlands of less than 30 ha are the most common, followed by mid-valley wetlands of similar size. This seems to be the case throughout the south-west highlands, although in the Jimma area the mid-valley wetlands tend to be larger on account of the less-dissected terrain (Afework Hailu, 2001). In Illubabor zone, government estimates suggest that valley-bottom wetlands account for approximately 1.4 per cent (22,677 ha) of the total land area (Table 2.2), although if this included other types of wetlands, such as floodplains, this would probably rise to approximately 5 per cent (82,775 ha) (Afework Hailu, Dixon, and Wood, 2000). The sedge *Cyperus latifolius*, known locally as *cheffe*, dominates most of the wetlands in their natural state, while larger wetlands are also fringed by the swamp palm *Phonex reclinata*. Whilst the larger wetlands remain inundated for most of the year, the smaller valley-head and mid-valley wetlands are inundated for varying lengths of time, sometimes for only four months during the height of the rainy season (Dixon, 2000).

Traditional use of Illubabor's wetlands and the development of local knowledge

Although wetlands are one of the minor land resources in south-west Ethiopia, they are a significant part of the resource base, being used by virtually every household in one way or another (Wood *et al.*, 1998). This is shown by the estimates given in Table 2.3, which are based on data obtained through a year of participatory rural appraisal (PRA) and other research activities in central Illubabor zone.

In western Wollega, to the north, highland wetlands are especially important for staple food production, given the degradation of the uplands as a result of *tef* cultivation on fragile soils. Hence, unlike other areas where wetland cultivation is a subsidiary source of food, most of the local cereal production in this area now comes from seasonal wetlands. In Jimma zone to the south of Illubabor, many wetlands have been degraded

Table 2.3 Wetland uses and beneficiaries in Illubabor

Uses	Estimate of households benefiting
Social/ceremonial use of sedges	100% (including urban dwellers)
Thatching sedges	85% (most rural households)
Temporary crop-guarding huts of sedges	30%
Dry-season grazing	Most cattle owners, c. 30% of population
Water for stock	Most cattle owners, c. 30% of population
Cultivation	25%
Domestic water from springs	50–100% (depending on the locality)
Craft materials (palm products and sedges)	5%
Medicinal plants	100% (mostly indirectly by purchase from collectors/traditional doctors)

and are used for dry-season grazing, although some remain in cultivation within the coffee forest areas. In the more forested areas there is less use of wetlands, but again at the southern edge of the south-west highlands, in the Keficho area, wetland cultivation with coco yams is found (Afework Hailu, 2001).

Wetland agriculture has a variable history in the south-west highlands. In some localities it has been practised for over 250 years according to local records. A special Oromifa word, *bonee*, derived from *bona* meaning dry time, exists to describe wetland cultivation, and this tends to confirm that wetland farming is an activity of some history. In parts of Illubabor zone the recent history of wetland cultivation is well known, the practice having been introduced (or reintroduced) in the early twentieth century in response to famine. This involved both exhortations by government administrators and advice from a local Muslim cleric who helped farmers experiment to find the appropriate pattern of drainage channels (Afework Hailu, 1998; Tegene Sishaw, 1998). However, this may build on older wetland cultivation practices, as it seems these areas were cultivated more than 100 years ago according to recent analysis of wetland cores (Belay Tegene and Hunt, 2000).

Wetland cultivation is primarily undertaken between January and June/July, during the latter half of the dry season and into the start of the rainy season (Figure 2.2). The green maize produced in this way makes an important contribution towards food security, as it is harvested in what is a hungry period (Abbot and Afework Hailu, 2001). Wetland use is often not uniform because of land rights and household resource constraints. As a result, within a single wetland there are usually a variety of uses ongoing, with some cultivation, beds of natural *cheffe* for collecting thatching, and areas used for seasonal grazing (Dixon, 2000).

The long history of wetland use has led to a considerable body of local knowledge being built up, and this contributes towards the sustainable use of these areas (Abbot and Afework Hailu, 1997; Tegene Sishaw, 1998; Dixon, 2000). Local people, especially wetland farmers, appear to have developed a variety of wetland management strategies and practices which meet their goals, particularly the long-term and sustainable use of these areas, in order to provide a number of wetland products and benefits in perpetuity (Table 2.3).

Wetland farmers recognize that flooding is the key to wetland sustainability for the various functions and products, including crops, they obtain from these areas. Flooding helps maintain fertility and controls the soil degradation processes associated with drainage, such as oxidation, mineralization, and compaction. Farmers employ a system of stream and drainage-channel blocking once the crop is harvested, in order to assist flooding, and this in turn helps the decomposition of crop residues, con-

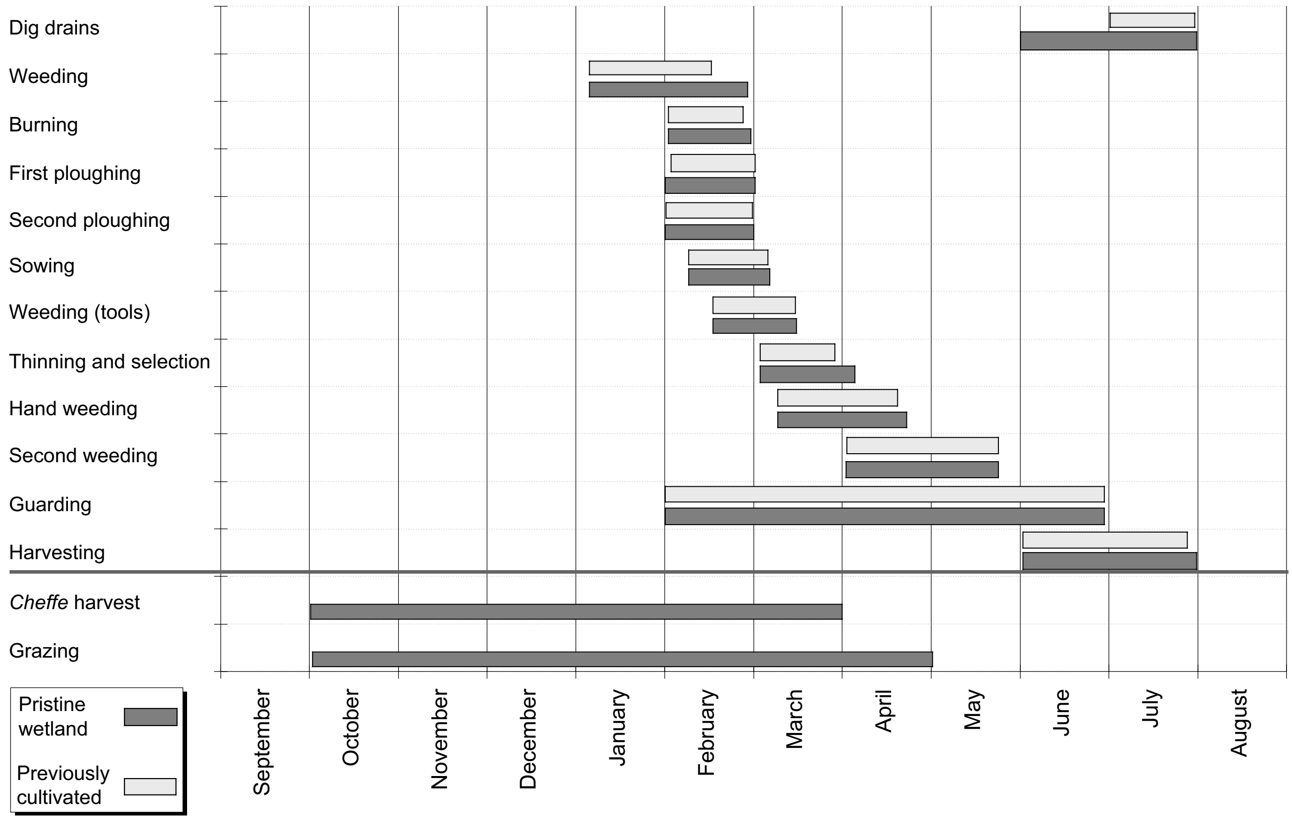

Figure 2.2 A typical seasonal calendar of wetland farming activities in the south-west highlands

trols weeds, and aids the recovery of the sedge vegetation. Blocking the drains is also recognized as a way to ensure the retention of catchment runoff and sediment which, during the rains, represents an important means of restoring the fertility of wetland soils (Tegene Sishaw, 1998; Afework Hailu, Abbot, and Wood, 2000; Dixon, 2000).

When wetland agriculture suffers from declining yields, farmers will abandon cultivation and block the drainage channels, leaving the area fallow for several years. Their understanding is that the re-establishment of the natural swamp vegetation will help rejuvenate soil fertility, and the quality of the *cheffe* is seen as an indicator of the recovery process. These farmers use soil colour, soil texture, and plant indicators to identify wetlands which will be suitable for drainage and cultivation in terms of fertility, moisture storage, and ease of drainage (Afework Hailu, Abbot, and Wood, 2000).

Hydrological knowledge amongst wetland cultivators is very detailed. They have a clear understanding of the seasonal rainfall and flooding regime, and know how to manage the water levels in wetlands in order to allow cultivation. Local adjustment of the depth and density of drains, and their layout, is undertaken in response to variations in soil conditions in different parts of the wetlands and the sources of water, such as springs, which locally affect the water table. Farmers also have extensive knowledge about the management of the drainage regime and the channels, with the lead-in times before cultivation well understood and also the need to block channels and raise the water table at certain times, especially just before sowing when it helps ensure germination (Dixon, 2000). Farmers also realize the importance of maintaining *cheffe* at the head and the outlet to retain water within the wetland and prevent downcutting.

With respect to sedges for thatching, farmers report that their quality varies depending upon their maturity. Where the wetlands have been disturbed for grazing or cultivation, the new sedges are poor for thatching and will last for only one or two years before having to be replaced. This is in contrast to mature sedges which will last for several years (Afework Hailu, 1998). This experience, as well as local shortage of sedges as a result of the cultivation and drainage of wetlands, has led some communities to establish local by-laws which protect established sedge beds and limit the extent of cultivation and grazing in the wetlands (Tegene Sishaw, 1998).

Some indigenous institutions have been developed to support the application of local knowledge. In the Tulla system of community administration, developed by the Oromo after they invaded part of the southwest highlands in the seventeenth century, one of the community elders was appointed as an Abba Laga, or "father of the water". This person was traditionally responsible for coordinating the use of the wetlands for a variety of purposes, including drainage agriculture. He had powers to organize drainage and guarding, and could also remove farmers from the wetlands if they were not farming in an appropriate manner (Afework Hailu, 1998; Abbot, Afework Hailu, and Wood, 2000).

Wetland development – Recent stimuli

Wetland development has been stimulated through the twentieth century by a number of factors. A key influence has been the technological development which allowed the progression from wetland margin drainage to full drainage of the smaller wetlands using a herringbone pattern of drains (see Figure 2.3) (Tafesse Asres, 1996). This technology was used initially by farmers in the first two decades of the twentieth century to respond to the demands from their landlords to increase crop production

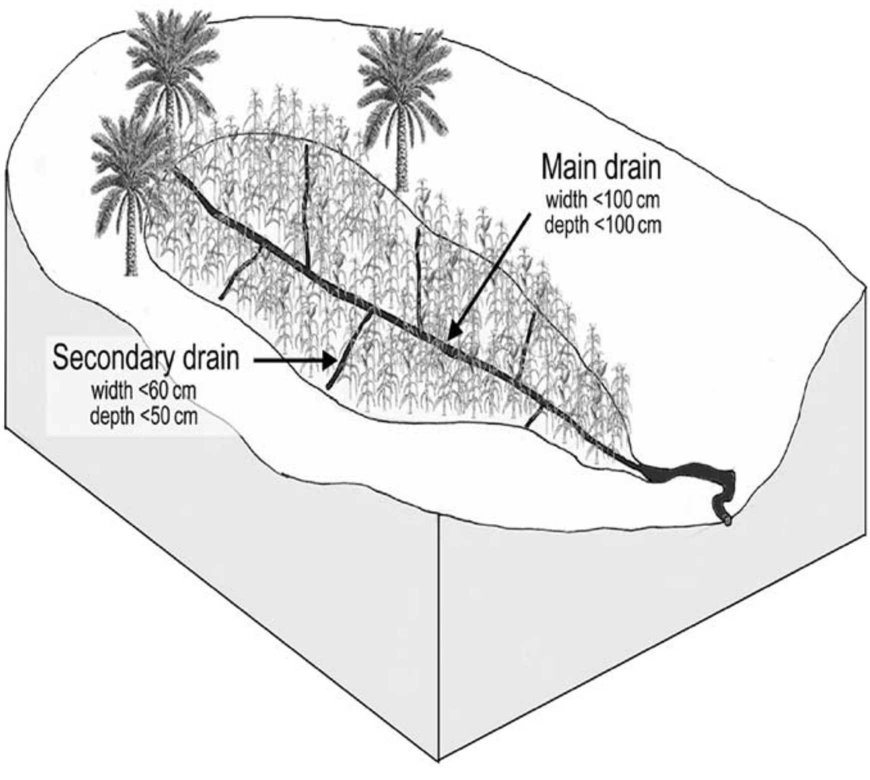

Figure 2.3 Complete drainage of a wetland

due to local food shortages caused by poor rainfall and pestilence. Later, landlords also demanded the cultivation of wetlands to release arable land on the interfluves for coffee planting. As a result, it is reported that wetland cultivation was developed most rapidly in this area during the latter part of Haile Selassie's reign (1930–1974) (Afework Hailu, 1998).

After the 1974 revolution, the socialist Derg[1] regime nationalized land and redistributed it to ensure greater equality of holdings amongst farmers. In Illubabor most households received some wetland plots and, as these would be redistributed again if not used, wetland cultivation expanded further, although with lower labour inputs and probably less careful management. More purposeful and intensive wetland cultivation was also encouraged at this time by some specific government actions, notably the introduction of quick-maturing maize varieties, which improved the success of wetland cultivation, and the distribution of the potato, a new crop which happened to be suited to wetland cultivation. There were also impacts upon wetlands from the severe 1984 famine in northern Ethiopia, which led to half a million famine victims being resettled to the south (Alemneh Dejene, 1990). In the south-west some of these settlers were allocated unwanted wetlands by local communities, and had to learn quickly how to manage these areas.

Other aspects of government policy have also affected wetlands. The extension policy, during the Derg period and since the 1991 change of government up to the time of writing, has stressed the need for improving food security. In the wetter south-west highlands the predominant response of micro-irrigation to achieve food security has been replaced by small-scale drainage of wetlands. This has been pursued with "vigour" in years when there have been poor harvests not just in the south-west but in any part of the country. To implement this policy, wetland task forces are established at the different administrative levels and each farming community is given a target requiring them to drain additional wetlands for cultivation.

Market forces have also had an impact on wetland cultivation, especially as urban centres have grown in this part of Ethiopia in connection with the coffee trade and other commercial activities. It appears that in the order of 30 per cent of the green maize grown in wetlands is marketed, in contrast to 10 per cent of the upland maize crop (Solomon Mulugeta *et al.*, 2000). Further, the urban markets for vegetables and *tef* have encouraged a few farmers to cultivate these crops as well in wetlands. This has been particularly dangerous for wetland sustainability as it has led to double cropping. This involves drainage beginning in August, during the rainy season, and cultivation taking place for eight or nine months from October/November to June/July. In this system, vegetables or *tef* are harvested in January before the maize is sown for harvesting in June/July. This obviously has serious implications for the hydrological regime and for the water-storage role of the wetlands.

Wetland development has been supported by NGOs in some areas. In one case in Illubabor zone, the cultivation of wetlands was encouraged as part of an eco-development programme which sought to reduce the amount of forest clearance by developing more intensive use of land outside the forested area (Wood, 1996).

Finally, a growing pressure upon wetlands comes from cattle. Although their number is not large, they are increasingly common in many localities in recent decades. This is probably in part a result of land reform, which has seen the richer members of society and those with coffee income invest in assets other than land. Certainly, there are several cases which show clearly how increased intensity of wetland grazing is facilitated by drainage and cultivation and how this can lead to the degradation of these areas, especially through soil compaction, and their abandonment for all uses except rough grazing (Afework Hailu, Abbot, and Wood, 2000).

Wetland development – Sustainable use or degradation?

Despite what appears to be a general intensification in wetland use in the south-west highlands in recent years, there is evidence of both the sustainable use of these areas and their severe degradation (Afework Hailu, Abbot, and Wood, 2000). Research findings suggest that degradation of wetlands is not only, or necessarily, linked to increasing intensities of use. Other factors such as catchment land use, wetland depth, and local geomorphological features play major roles in determining the eco-hydrological characteristics of each wetland, and hence their capacity to support different forms of wetland use (Dixon, 2000; Afework Hailu, Abbot, and Wood, 2000).

The local knowledge and experience of farmers and wetland communities are critical in determining whether there is sustainable or unsustainable wetland use. For example, one wetland in Illubabor zone which has been drained and cultivated each year for over 80 years shows little sign of environmental degradation. Discussions with farmers at this site revealed that a well-developed local wetland knowledge system exists through which farmers have accumulated and developed an extensive repertoire of wetland management techniques that are adapted to their local environmental conditions. Critically, cooperation among the wetland farming community was also found to be high – an important prerequisite for the labour-intensive tasks involved in the wetland cultivation calendar and for water management, while some by-laws had been developed to prevent overdrainage of the wetland and protect some areas of *cheffe*.

However, local wetland knowledge is not always adequate to ensure sustainable use, and in some sites there has been overdrainage leading to the abandonment of cultivation and wetland product collection. This sort of problem may sometimes be the result of a lack of adaptation of local knowledge to different sites, to larger areas of drainage, and to different labour resource situations. Possessing the capacity to address and adapt local knowledge to new environmental and socio-economic circumstances may be a problem, especially if farmers are restricted by time and resources in their acquisition or development of new wetland knowledge and skills. In wetlands where drainage and cultivation has a short history, and particularly where wetland cultivation has been imposed suddenly upon a community, degradation is a common phenomenon. This is arguably because wetland use under these circumstances does not build upon, develop, or incorporate indigenous practices and local knowledge (Wood, 1996; Afework Hailu, Abbot, and Wood, 2000; Dixon, 2000).

Wetland degradation also often occurs where there are strong economic or political pressures which lead to the complete drainage of the wetland and sometimes also the adoption of double cropping. This is often associated with the development of market opportunities, or with the enforced cultivation of wetlands in response to the government food security drive by the wetland task forces. Further examples of wetland degradation are associated with the introduction of new technologies by external agencies, such as NGOs, without consultation with the local communities and so without reference to local experience of wetland management. Lack of local institutional capacity seems to be another regular problem, for instance where there are not adequate methods for controlling the use of wetlands. Overdrainage, extensive drainage, and lack of control over cattle grazing are all problems which in successful cases are controlled by communities through wetland by-laws and management committees, but are neglected in cases of degradation. Hence, where communities have little experience of wetland agriculture, or when conditions change and local knowledge and management practices have not adapted, wetland degradation can occur very rapidly.

In the south-west highlands the degraded wetlands typically exhibit extremely variability in their water-table levels, and this is linked to the physical and chemical degradation of wetland soils as a result of excessive drainage, cultivation, and animal grazing (Conway and Dixon, 2000; Belay Tegene and Hunt, 2000). These areas tend to lack any of the key wetland characteristics, such as sedge vegetation or saturated, fertile soils, and, as a result, they are unable to support any of the functions and benefits associated with undrained or carefully managed wetlands. Their ability to provide water storage is also greatly reduced. Communities with degraded wetlands report that many springs have dried up and that the quality of water has been affected by an increase in sediment load (Afework Hailu, Abbot, and Wood, 2000; Shields, 2001). In addition, the increasingly ephemeral nature of the outflow streams has had far-reaching consequences for those lower down the catchment in terms of water supply and flooding. In the Baro River basin, in particular, communities in the lowlands have suffered from abnormal flooding at one time and a shortage of clean drinking water at another, both as a result of human interference and poor land-use management in the upstream areas (Mengistu Woube, 1999). Further, within the highland the hydropower barrage on the Sor River has suffered from inadequate flows in the dry season in two recent years, a phenomenon which is often attributed to wetland degradation as well as forest clearance.

Wetlands in Rwanda

In Rwanda wetlands are an important element in the landscape and the hydrological system. They account for approximately 6.3 per cent of the surface area. There are various different types of wetlands, broadly categorized by their association with a particular altitudinal zone, with peat bogs at higher altitudes, papyrus swamps and floodplains at lower altitudes, and seasonal valley wetlands in the mid-altitude zone (1,400 m to 2,000 m) (Kanyarukiga and Ngarambe, 1998).

With an average population density of 317 inhabitants per square kilometre, and growing at 3 per cent per annum, Rwanda is the most densely populated country in mainland Africa. Approximately 92 per cent of the population are engaged in agriculture, the majority of which is subsistence oriented. Pressure on land is severe, and the average farm size is less than one hectare, about half of which (0.55 ha) is cultivable. High population pressure, coupled with land scarcity, has resulted in the cultivation of increasingly marginal lands, particularly very steep, fragile slopes which are highly susceptible to erosion. This has led to increased land degradation, including loss of soil fertility, serious erosion problems, and a reduction in yields and productivity, with the result that the food security needs of the Rwandan people are not met. As a result, there has been an intensification in the use of valley-bottom wetlands for agriculture.

Agricultural use is most common in the mid-altitude wetlands of Rwanda and is apparently of more recent origin than that of south-west Ethiopia. However, there are indications that wetland use has evolved rapidly in some parts of Rwanda over the last two decades. This has seen a change from limited dry-season use of the wetlands for a single crop to double cropping with both wet- and dry-season use. This has occurred partly in response to local initiatives, but has been primarily as a result of government and NGO-led initiatives seeking to address chronic food security problems. These initiatives, however, have usually focused on the technical aspects of drainage and irrigation, so that many developed wetlands are characterized by the presence of permanent hydrological control structures, such as micro-barrages, deep drainage channels, and shallower irrigation channels, some of which are constructed in concrete. Meanwhile, other experimental initiatives are exploring the potential for fishpond development in some of the larger wetlands.

The double cropping has created a variety of problems within the wetlands, with excess water in the wet season leading to crop damage and downcutting in the wetlands. In contrast, in the dry season, despite the new irrigation channels, there is now insufficient water for cultivation, apparently because of the very deep drainage channels required for wet-season cultivation. The double-cropping regime also has implications for streamflow variability, as the intensive drainage regimes rapidly convey water through the wetlands, disrupting their natural storage capacity and hydrological regulatory functions.

The initiatives for wetland drainage are being supported actively by the Rwandan government and many NGOs at present because of the concern about developing economic security for all sections of the Rwandan population. The wetlands are seen as one of the few agricultural resources which are not fully developed. Many of these areas are under state control, not being part of the traditional land management regime, and so are rented out at a local level to land-scarce farmers. These farmers may be part of farmers' groups who manage these areas, thus slowly experience and knowledge about wetland use are being built up.

As yet this practice of double cropping is of limited extent, probably totalling only some 6,000 ha of the total 94,000 ha of wetland developed for agriculture, and less than 4 per cent of the total wetland area (GoR, 2000a; Kanyarukiga and Ngarambe, 1998). However, there are great pressures to develop the wetlands of Rwanda further for food security and economic reasons, and this is a major thrust in the government policy and is included in the newly launched Rural Sector Support Programme (RSSP). The ecological implications of this are not entirely neglected in the RSSP, and it has been recognized that there is a need to address the potential conflict between environmental rehabilitation for sustaining production and ecologically insensitive development. As a result a GEF project has been formulated to look at ways in which the environmental implications of intensified agricultural development can be ameliorated

(GoR, 2000b). This will include the development of a national wetland policy and the development of improved land-use management for wetlands in an attempt to address the ecological problems faced in agricultural intensification.

At the same time the pressures to increase the area of wetland under double cropping has led to attempts to identify ways in which the water can be better managed so that higher-value crops can be cultivated, rather than the sweet potato which, due to its resistance to floods, tends to dominate the wetlands. Water control is being sought in some cases through dam construction in the catchments to store water for dry-season use and to ameliorate the flood levels in the wet season. However, the economic viability of these proposals and their widespread applicability are doubted, and alternative methods for improved wetland management need to be considered.

The key danger in Rwanda is that if wetland cultivation develops further without addressing the issues of hydrological and agricultural sustainability, the wetland resources of this country will be seriously degraded and their contribution to national food and water security will be dramatically reduced. There is, therefore, an urgent need to develop ways of managing wetlands so that the long-term needs of communities and the wider hydrological system are realized and met. The suggestion here is that these two could be mutually beneficial and ultimately lead to a state of sustainable wetland use in which a range of wetland goods, services, and functions are available to numerous beneficiaries and stakeholders.

Towards sustainable wetland use

In both Ethiopia and Rwanda there has been increasing pressure on wetland resources for various reasons. While in Ethiopia the scenario is one where low-intensity, traditional wetland management practices are being replaced by more intensive ones, the situation in Rwanda involves more radical intensification of use of wetlands in specific areas. In both cases, the danger is that wetland development will have wide-ranging impacts upon the hydrological regime both locally and downstream, and on the sustainability of wetland use and hence the availability of wetland products and functions. To avoid these negative developments and establish a form of sustainable wetland use which maintains the various benefits from these areas, there is a need to explore the ecological and hydrological functioning of these areas and the limits to which they can be altered whilst still retaining their essential functioning as wetlands. Further, it is necessary to develop appropriate institutions which will ensure the involvement of all stakeholders in the development of locally appropriate and sustainable wetland management regimes.

In south-west Ethiopia, among the range of indigenously developed wetland management practices, several appear to make critical contributions to sustainable wetland use and can help maintain hydrological functioning. The practice of retaining areas of natural vegetation in cultivated wetlands, alongside the drained and cultivated plots and especially at the wetland head and outflow, is a way of maintaining the optimum water-table levels for crop production whilst also mitigating the effects of drainage on the hydrological functioning of the wetlands. In addition, the practice of ensuring the flooding of whole wetlands, either at the end of the cultivation period or for longer periods, is also critical for wetland regeneration. This facilitates the restoration of soil structure and fertility, the regeneration of the natural sedge vegetation, and the recovery of the water-table levels. Overall, this rejuvenates the wetlands and their capacity to store and regulate water supplies.

A key concept in this management process is the establishment of multiple land use within wetlands, with areas of natural wetland alongside areas which are drained and cultivated, and others which are used for either controlled grazing or the collection of natural products (Howard, Bakema, and Wood, in press). This multiple use can be operationalized on a spatial or temporal scale, either by maintaining different types of land use within a wetland at one time and rotating these so that no area has permanent drainage, or else by introducing fallow periods for the whole wetland for a number of years to allow *cheffe* regeneration to take place (Figure 2.4).

However, faced with increasing socio-economic, environmental, and political pressures, the use of local knowledge and traditional practices alone may not be able to guarantee the sustainable use of all the different types of wetlands and the maintenance of their various wetland functions and benefits. If local wetland knowledge and practices are to develop and adapt to cope with the evolving situation, the institutions and mechanisms through which that knowledge is accumulated and disseminated need to be strengthened and empowered. This may require the interaction of local and external expertise in a similar manner to the loop concept proposed by Ryden (1992). This would involve all wetland stakeholders identifying the problems they face, and with their existing knowledge trying to address these issues. Then, for outstanding problems, external expertise would be used to support local problem-solving processes, thereby strengthening the capacity of the local communities to develop their own solutions to problems. Through the development of local capacity, and especially local natural resource management institutions, further adaptive wetland management strategies could evolve primarily from

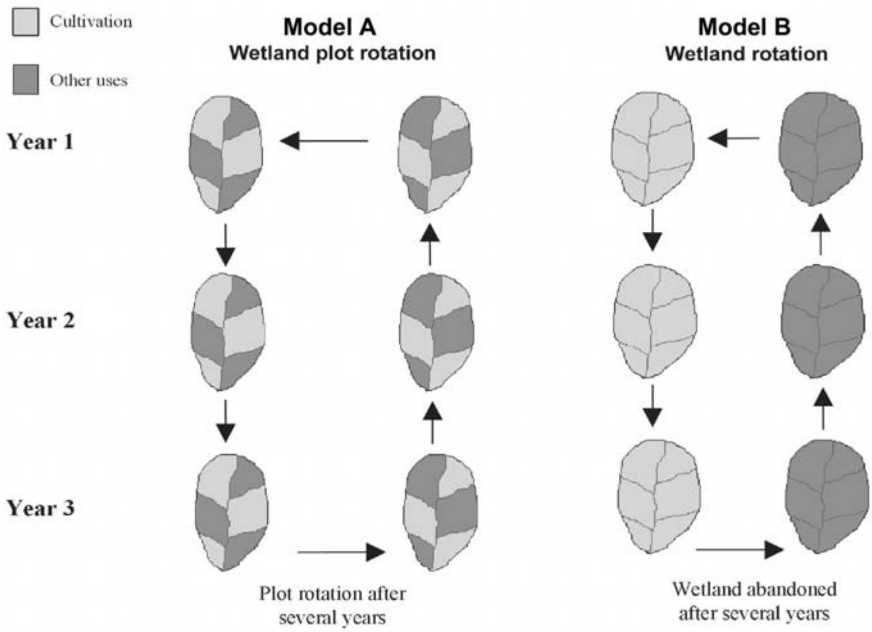

Figure 2.4 Maintaining the multiple uses of wetlands

within the community to ensure that they are both ecologically and socio-economically sustainable (Dixon, 2000).

The key to this institutional and knowledge development is the exchange of information and experience. While this occurs to some extent through weekly markets and similar gatherings, these appear to be inadequate means of information dissemination (Dixon, 2000). Recent experience from farmer exchange visits organized by the Ethiopian Wetlands Research Programme (EWRP) has shown that these may be an important method for achieving the rapid transfer of information. In addition, that programme has also developed community-level extension materials based on farmers' experiences rather than on textbook advice (Afework Hailu, Abbot, and Wood, 2000). This is now being used by a new NGO, the Ethio Wetlands and Natural Resources Association (EWNRA), which is working with local communities to improve understanding of wetland management. It is also helping to retrain government extension staff so that they are more sensitive to wetland realities, rather than simply accepting the top-down commands of the wetland task forces. This training work has also involved helping the local agriculture departments appoint wetland officers for each district to monitor the changes in wetlands, so that hopefully with time feedback to policy-making levels will lead to the formulation of more sensitive policies.

Another key lesson from the Ethiopian experience is the need for institutional development for wetland management. In several parts of southwest Ethiopia communities have developed their own management regimes for wetlands with by-laws developed to control drainage, reed cutting, and grazing. In western Wollega, where wetlands are so important for food security, wetland management coordinating committees (WMCCs) have been widely established based on the traditional Abba Laga system (Afework Hailu, 2001). However, there appears to be limited representation in these committees, which are dominated by the wetland farmers and include few of the other stakeholders with interests in these areas and their products. In particular there is a neglect of women with their interests in the maintenance of wetland fringe springs, which in turn have wider hydrological implications (Shields, 2001). As a result it may be noted that more democratic representation is needed in these institutions to ensure their long-term success (Abbot, Afework Hailu, and Wood, 2000).

Such local institutions are also the basis for managing the external pressures on wetlands (whether they come from government policies or from market forces) which encourage excessive drainage of these areas and their degradation into rough grazing areas. Whether it be the government wetland task forces or the pressure from rich farmers to respond to market opportunities by appropriating community wetland resources, these pressures need to be managed by communities, through WMCCs or the like, to ensure that some wetland uses are not expanded in direct contradiction to locally recognized best practice and to the detriment of both the long-term sustainable use of these areas and their hydrological functioning.

In Rwanda the experience of wetland management is less fully collated, although there is considerable information about the extent of wetlands and their use (Kanyarukiga and Ngarambe, 1998). A key starting point for understanding current wetland management is to identify the local expertise and the wetland dynamics which exist, and then explore how the ecological characteristics of wetlands can be manipulated in a mimimal way in order to allow productive uses whilst maintaining hydrological functioning. One crucial aspect of wetland use in Rwanda is the extent to which crop damage as a result of rain-induced flooding can be ameliorated, and the potential role of wetland head swampland or other measures in mitigating the impact of this. Similarly, there is a need for research to identify the role of drainage channels, particularly different drainage layouts, in facilitating the hydrological recharge of different parts of wetlands in the dry seasons, as well as reducing moisture excess in the rainy seasons. The use of drain blocking and other water management techniques seems to have a potential for improved micro-hydrological management. The role of natural wetland vegetation as part of a rotational drainage and cultivation system also needs to be explored with respect to the maintenance of soil fertility and crop productivity. There are also questions regarding the capacity of catchments when under different land uses to store water, regulate runoff, and contribute to the hydrological regime of wetlands. The size, geomorphology, and land use of catchments all play critical roles in determining the hydrological regime, hence wetland management issues go beyond the wetlands themselves here and in Ethiopia.

Conclusion

It has been recognized for many decades that wetland degradation is an increasingly widespread problem in many parts of the world (Ramsar Bureau, 1971), especially in developing countries (Hollis, 1990; Dries, 1991; Roggeri, 1998). Wetland degradation is also now becoming a common phenomenon in tropical highland areas, with many recent reports of this from Eastern Africa, notably from Rwanda, Kenya, Uganda, and Ethiopia (Kanangire, in press; Gichuki, 1992; Denny and Turyatunga, 1992; Howard, Bakema, and Wood, in press; Wood, 1999). Unless appropriate action is taken soon, the ability of upland areas to continue to function as water-towers for their surrounding areas will be seriously impaired. Hence improvements in the management of headwater wetlands and their catchments have to be given urgent attention.

Some of the steps which are required to ensure that wetlands retain their key water-storage capacity have been discussed above with respect to the Ethiopian and Rwandan experience. They can be reviewed in order to identify generic steps needed to achieve forms of sustainable wetland use which meet both local needs and wider hydrological ones.

The first step will focus on awareness-raising in order to place the issue of wetland management on the local and national agendas for action. This must stress the special characteristics and contributions of wetlands and ensure that they are understood and considered at all levels. This awareness-raising should be supported by exploratory research and information dissemination to help identify the uses of wetlands and the various stakeholders who are involved. Part of this research must be directed to understanding the ecological dynamics of these areas to identify the limits for their transformation and appropriate land-use regimes. Once such guiding limits have been identified, a land-use model, almost certainly a multiple-use model, can be developed to ensure that wetlands continue to operate as water-storage areas for local and wider benefit, as well as meeting other local needs. Linked to the research and land-use modelling must be a process of identifying the indigenous practices which are likely to support sustainable use and those which have negative impacts upon sustainability. From this it will be possible to identify gaps in the knowledge base which require external support or new on-site research.

Sustainable wetland management also requires the development of local institutions, policies, and by-laws which can coordinate the use and management of wetlands and their catchments. Such institutions should be linked into local community structures, but should be at the lowest possible level so there is a clear sense of ownership over the necessary by-laws and regulations which communities create. They should also be democratic institutions so that local élites do not appropriate wetlands for their own usually single purpose, thereby limiting the contributions of these areas in terms of products and functions for the local and wider communities, including sustaining river flow.

Such local democracy needs to be informed and if necessary managed to ensure that the interests of both downstream and upstream communities are included. This may require higher-level intervention of a district or regional nature. However, care must be exercised to ensure that such interventions do not undermine the local sense of responsibility towards such areas. Indeed, a guiding principle in developing sustainable wetland management must be that local communities gain benefits from their wetlands so that they have vested interests in protecting these areas and ensuring their sustainable functioning. To ensure the water-storage role of highland wetlands there need to be demonstrable benefits, such as perennial clean spring water and craft or medicinal materials, which are incentives for communities to maintain an appropriate land-use regime in these areas.

Local wetland management institutions are also an important means of ensuring that the pressures on wetland communities to overdevelop and degrade these areas do not become too great. These institutions may well need to be strengthened so that they are able to stand up to government pressures. At the same time, governments need to undertake environmental assessments of their policies to find out how they impact upon wetlands and amend these policies accordingly (Wood, 2000).

In the wider perspective, this work on wetland management will only be successful in sustaining the flow of the Nile if there is multi-country coordination, and perhaps outline planning, to try to develop appropriate land use along the Nile and its various tributaries in both their watersheds and their valley bottoms. While some strategic planning could be undertaken, the most effective initiative is likely to be policy development to encourage appropriate land use by communities along these river systems. In this respect policies and techniques which promote sustainable wetland use are two further key elements for sustaining the flow of the Nile.

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Notes

1. The term "Derg" refers to the government of Ethiopia between 1974 and 1991, in which power was initially shared by a military committee and later centralized into the hands of President Mengistu Haile Mariam.

REFERENCES

Abbot, P. G. and Afework Hailu (eds). 1997. "Report on the PRA training workshop for sustainable wetland management in Illubabor zone, Metu, 10–21 November", unpublished mimeo. Metu: EWRP.

Abbot, P. G. and Afework Hailu. 2001. "Wetlands and food security in southwest Ethiopia", EWRP Policy Briefing Notes 4. Metu and Huddersfield: EWRP/University of Huddersfield.

Abbot, P. G., Afework Hailu, and A. P. Wood. 2000. "Community organisation for natural resource management and the potential for community-based wetland management'', Report 2 for Objective 3. Metu and Huddersfield: EWRP/University of Huddersfield.

Adams, W. M. 1993. ''Indigenous use of wetlands and sustainable development in West Africa'', *Geographical Journal*, Vol. 159, No. 2, pp. 209–218.

Afework Hailu. 1998. ''An overview of wetland use in Illubabor'', unpublished mimeo. Metu: EWRP.

Afework Hailu. 2001. ''An overview of wetland use in south-west Ethiopia'', unpublished mimeo. Metu: EWRP.

Afework Hailu, A. B. Dixon, and A. P. Wood. 2000. ''Nature, extent and trends in wetland drainage and use in Illubabor zone, south-west Ethiopia'', Report for Objective 1. Metu and Huddersfield: EWRP/University of Huddersfield.

Afework Hailu, P. G. Abbot, and A. P. Wood. 2000. ''Appropriate techniques for sustainable wetland management'', Report for Objective 4. Metu and Huddersfield: EWRP/University of Huddersfield.

Alemneh Dejene. 1990. *Environment, Famine and Politics in Ethiopia: A View from the Village.* Boulder, CO, and London: Lynne Reinner.

Amatya, D. M., G. M. Chescheir, and R. W. Skaggs. 1995. ''Hydrologic effects of wetland location and size in an agricultural landscape'', in K. L. Campbell (ed.) *Versatility of Wetlands in the Agricultural Landscape*, Proceedings of AWRA Conference, Tampa, Florida, 17–20 September. Tampa: ASAE, pp. 477–488.

Balek, J. and J. E. Perry. 1973. ''Hydrology of seasonally inundated African headwater swamps'', *Journal of Hydrology*, Vol. 19, pp. 227–249.

Belay Tegene and C. O. Hunt. 2000. ''The characteristics and management of wetland soils of Metu Wereda, Illubabor zone of Oromia region'', Report 2 for Objective 2. Metu and Huddersfield: EWRP/University of Huddersfield.

Conway, D. and A. B. Dixon. 2000. ''The hydrology of wetlands in Illubabor zone'', Report 1 for Objective 3. Metu and Huddersfield: EWRP/University of Huddersfield.

Denny, P. and F. Turyatunga. 1992. ''Ugandan wetlands and their management'', in E. Maltby, P. J. Dugan, and J. C. Lefeuvre (eds) *Conservation and Development: The Sustainable Use of Wetland Resources*, Proceedings of the Third International Wetlands Conference, Rennes, France, 19–23 September. Gland: IUCN, pp. 77–84.

Dixon, A. B. 2000. ''Indigenous knowledge and the hydrological management of wetlands in Illubabor, Ethiopia'', PhD thesis, University of Huddersfield.

Dries, I. 1991. ''Development of wetlands in Sierra Leone: Farmers' rationality opposed to government policy'', *Landscape and Urban Planning*, Vol. 20, pp. 223–229.

Dugan, P. J. 1990. *Wetland Conservation: A Review of Current Issues and Action.* Gland: IUCN.

FAO. 1986. *Ethiopian Highland Reclamation Study, Ethiopia. Final Report.* Rome: FAO.

Gichuki, F. N. 1992. ''Utilisation and conservation of wetlands: An agricultural drainage perspective'', in S. A. Crafter, S. G. Njuguna, and G. W. Howard (eds) *Wetlands of Kenya*, Proceedings of the KWWG Seminar on Wetlands of Kenya, Nairobi, Kenya, 3–5 July 1991. Gland: IUCN, pp. 147–154.

GoR (Government of Rwanda). 2000a. *Rural Sector Support Programme*. Kigali: GoR.

GoR (Government of Rwanda). 2000b. *Integrated Protection and Management of Critical Ecosystems*, GEF project proposal. Kigali: GoR.

Grab, S. and C. Morris. 1999. ''Soil and water resource issues of the eastern alpine belt wetlands in Lesotho'', in H. Hurni and J. Ramamonjisoa (eds) *African Mountain Development in a Changing World*. Madagascar: African Mountains Association, pp. 207–219.

Hollis, G. E. 1990. ''Environmental impacts of development on wetlands in arid and semi-arid lands'', *Hydrological Sciences Journal*, Vol. 35, No. 4, pp. 411–428.

Hollis, G. E., W. M. Adams, and M. Aminu-Kano. 1993. *The Hadejia-Nguru Wetlands: Environment, Economy and Sustainable Development of a Sahelian Floodplain*. Gland: IUCN.

Howard, G. W., R. J. Bakema, and A. P. Wood. In press. ''The multiple use of wetlands in Africa'', in E. Maltby (ed.) *The Wetland Handbook*. Oxford: Blackwell.

Kanangire, C. In press. *Proceedings of the First Seminar on the Management of Wetlands in Rwanda, 5–7 June 2001*. Butare: National University of Rwanda.

Kanyarukiga, S. G. and V. Ngarambe. 1998. ''Rwanda country paper: The agricultural characterisation and classification of wetlands'', paper for FAO workshop. Kigali: MINAGRI, available at www.fao.org/DOCREP/.

Kumelachew Yeshitela. 1997. ''An ecological study of the forest vegetation of south-western Ethiopia'', MSc thesis, Addis Ababa University.

Lema, A. J. 1996. ''Cultivating the valleys: Vinyungu farming in Tanzania'', in C. Reij, I. Scoones, and C. Toulmin (eds) *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa.* London: Earthscan, pp. 139–144.

Maltby, E. 1986. *Waterlogged Wealth: Why Waste the World's Wet Places?*. London: Earthscan/IIED.

Mengistu Woube. 1999. ''Flooding and sustainable land-water management in the lower Baro-Akobo river basin, Ethiopia'', *Applied Geography*, Vol. 19, pp. 235–251.

Million Alemayehu. 1996. ''Traditional ditches in northern Shewa, the Ethiopian highlands'', in C. Reij, I. Scoones, and C. Toulmin (eds) *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa.* London: Earthscan, pp. 163–169.

Mountain Agenda. 1998. *Mountains of the World: Water-towers for the 21st Century*. Berne: Mountain Agenda.

Newson, M. 1992. *Land, Water and Development: River Basin Systems and their Sustainable Management.* London: Routledge.

Newson, M. 1994. *Hydrology and the River Environment.* Oxford: Oxford University Press.

Noble, R. 1996. ''Wetland management in Malawi as a focal point for ecologically sound agriculture'', *ILEA Newsletter*, Vol. 12, No. 2. p. 9.

Ramsar Bureau. 1971. *Proceeding of the International Conference on Conservation of Wetlands and Waterfowl, Ramsar, Iran, 30 January–3 February*. Slimbridge: International Wildfowl Research Bureau.

Roggeri, H. 1998. *Tropical Freshwater Wetlands: A Guide to Current Knowledge and Sustainable Management*. Dordrecht: Kluwer Academic Publishers.

Reusing, M. 1998. ''Monitoring of natural high forests in Ethiopia. A report prepared for Government of the Federal Democratic Republic of Ethiopia Ministry of Agriculture (MoA) and German Agency for Technical Co-operation, GTZ'', mimeo. Addis Ababa: Ministry of Agriculture.

Ryden, P. 1992. ''The IUCN approach in the Sahel'', in A. P. Wood and P. Ryden (eds) *The IUCN Sahel Studies 1992*. Gland: IUCN, pp. 1–5.

Shields, A. 2001. *Gender Relations and the Sustainable Management of Wetlands in Illubabor Zone, South-west Ethiopia*. Huddersfield: Wetland Action.

Solomon Mulugeta, P. G. Abbot, Tegene Sishaw, and Afework Hailu. 2000. ''Socio-economic determinants of wetland use in the Metu and Yayu Hurumu weredas of Illubabor'', Report 1 for Objective 3. Metu and Huddersfield: EWRP/University of Huddersfield.

TAMS-ULG. 1996. ''Baro-Akobo river basin integrated development master plan project: Final report'', unpublished consultancy report for the Ministry of Water Resources, Addis Ababa.

Tafesse Asres. 1996. *Agro-ecological Zones of South-west Ethiopia*. Addis Ababa: Addis Ababa University Press.

Tegegne Sishaw. 1998. ''Socio-economic aspects of land use change and wetland utilisation in two communities in Illubabor zone'', MSc thesis, University of Addis Ababa.

Wood, A. P. 1996. ''Wetland drainage and management in south-west Ethiopia: Some environmental experiences of an NGO'', in A. Reenburg, H. S. Marcusen, and I. Nielsen (eds) *The Sahel Workshop 1996*. Copenhagen: Institute of Geography, University of Copenhagen, pp. 119–136.

Wood, A. P. 1999. ''Wetlands in highlands: The search for sustainable management of wetlands in Illubabor zone, south-west Ethiopia'', in H. Hurni and J. Ramamonjisoa (eds) *African Mountains and Environmental Management*. Berne: African Mountains Association and Geographica Bernensia, pp. 305–320.

Wood, A. P. 2000. *Policy Issues in Sustainable Wetland Management*. Report for Objective 6. Metu and Huddersfield: EWRP/University of Huddersfield.

Wood, A. P., Afework Hailu, P. G. Abbot, and A. B. Dixon. 1998. ''Sustainable management of wetlands: Local knowledge versus government policy'', paper presented at the Second International Conference on Wetlands and Development, Dakar, Senegal, 8–14 November.

Woodhouse, P., H. Bernstein, and D. Hulme. 2000. *African Enclosures? The Social Dynamics of Wetlands in Drylands*. Oxford: James Currey.

Zimmerer, K. S. 1991. ''Wetland production and smallholder persistence: Agricultural change in a highland Peruvian region'', *Annals of the Association of American Geographers*, Vol. 81, No. 3, pp. 443–463.

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The sustainable management of headwater wetlands: The role of indigenous knowledge in south-west Ethiopia

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Introduction

Wetlands are important resources in headwater areas, where they provide a range of environmental functions and socio-economic benefits for local and downstream communities. Because of their key contribution to food and water security there is a need to manage wetlands in an environmentally sustainable manner so that their associated functions and benefits can be sustained. This need is particularly pressing given that land shortages, population increases, and government policies throughout the developing world have increased the pressure to exploit wetlands for agriculture.

Using a case study from south-west Ethiopia, this chapter argues that local communities and their indigenous knowledge have a central role to play in achieving the environmental and socially sustainable management of wetlands in headwater areas. In Illubabor zone, south-west Ethiopia, local communities have built up considerable knowledge of the dynamics of wetlands, including vegetation, soils, geomorphology, and hydrology. Much of this knowledge is used by these communities to identify major changes which are taking place in wetland ecology and, therefore, contributes to decision-making about the management of these areas. While this knowledge is not formalized or uniformly distributed, it is a key resource which should be recognized and incorporated in a more participatory wetland management and planning process. The chapter suggests that indigenous knowledge (IK) must evolve in order to face the challenges of growing local and external pressures on wetlands, and that some empowerment of IK resources within wetland communities may be necessary to facilitate community-based sustainable wetland management.

There has been a growing recognition of the importance of wetlands in terms of both their biodiversity and the range of functions and products they provide for human populations (Dugan, 1990; Hollis, 1990; Denny, 1994; Mitsch, 1994; Roggeri, 1998). In particular, economic appraisals of natural wetland functions and benefits have suggested that the advantages of maintaining wetlands in their natural state outweigh those of converting or developing them for agriculture or commercially viable land (Turner, 1991; Barbier, 1993; Barbier, Acreman, and Knowler, 1997). Consequently there has been a move towards the conservation of natural wetland functions and values, with the Ramsar Convention advocating the principles of "wise use" and "sustainable utilization" of wetlands and their resources (Davis, 1993; Ramsar Convention Bureau, 2000b).

Whilst such approaches have recognized the dependence of local communities on wetlands, little attention has been given to the knowledge on which indigenous practices are based – knowledge which has in the past been regarded as outdated, unproductive, and disorganized (Agrawal, 1995). The concept of community involvement has been synonymous with community cooperation in achieving conservation-oriented management goals, rather than the incorporation and empowerment of indigenous knowledge and community control over wetland management strategies (Claridge and Callahan, 1997). In many parts of the developing world, however, wetlands remain a critical source of food for both humans and livestock (Scoones, 1990; Barbier, 1993; Adams, 1993; Lema, 1996). Although in current development frameworks the conversion of wetlands for agricultural use may be inevitable, this may not always sustain their productivity in the long term. In Illubabor zone, however, the Oromo communities that migrated to the area during the eighteenth century have, in a relatively short space of time, developed indigenous knowledge systems which support the sustainable use of agricultural resources (McCann, 1995; Dixon, 2000).

This chapter discusses the significance of indigenous knowledge in the management of wetlands in Illubabor zone, south-west Ethiopia. Wetlands are abundant throughout this area and their utilization for both natural resources and agriculture is widespread, but there has been some concern that the recent overexploitation of wetlands may be threatening their long-term ability to provide a range of functions and benefits (Kebede Tato, 1993; Butcher and Wood, 1995; Wood, 1996; Afework Hailu, Abbot, and Wood, 2000). The chapter also reviews the evidence to suggest that the effects of overexploitation are being avoided, mainly by the application of indigenous knowledge in a range of technologies and management practices.

Indigenous knowledge

With increasing recognition of the various problems associated with the transfer of Western-style top-down approaches to development in the developing world, researchers since the late 1970s have placed increasing significance on the role of indigenous knowledge (IK) in sustainable natural resource management (Brokensha, Warren, and Werner, 1980; Chambers, Pacey, and Thrupp, 1989; Scoones and Thompson, 1994; Warren, Slikkerveer, and Brokensha, 1995). IK is commonly regarded as rural people's knowledge, characterized by ideas and practices that have evolved over time through a gradual learning process which has emerged from observation, experimentation, and the handing down of information from one generation to the next (Chambers, 1983).

With this recognition of the dynamic and evolving nature of IK, researchers and practitioners in the field of rural development have tended to focus more on local communities as researchers and resource managers, rather than being passive adopters of external ideas and technologies. Much research during the past 20 years has focused specifically on the role of farmers as innovators and experimenters who, in response to social or environmental pressures, actively seek solutions to their resource management or agricultural problems (Richards, 1985; Chambers, Pacey, and Thrupp, 1989; Rhoades and Bebbington, 1995). In addition, research has also focused on the acquisition and spread of IK through indigenous communication channels (Winarto, 1994; McCorkle and McClure, 1995; Mundy and Compton, 1995). Through a continuous process of innovation, communication, and adaptation, the acquisition and evolution of IK is considered a critical mechanism in achieving the environmental and social sustainability of resource use (Warren and Cashman, 1988; Rajasekaran, 1993; De Walt, 1994; Haverkort and Hiemstra, 1999). Fielding and Kirsopp-Reed (1994), in particular, suggest that IK has sustained local communities for generations, particularly those who have yet to meet any extension agents.

Whilst IK has been identified as playing a key role in the success and sustainability of resource management strategies, its influence and inclusion in policy has tended to be limited to agricultural research and planning, with an emphasis on farmer participation in agricultural extension (Chambers, Pacey, and Thrupp, 1989; McCorkle, 1989; Warren, 1991; Scoones and Thompson, 1994). In the case of wetlands, where conservation of the wetland habitat has dominated the international agenda, the concept of IK and community participation in wetland management is a relatively recent phenomenon (Marchand and Udo, 1989; Claridge and Callahan, 1997; Ramsar Convention Bureau, 2000a). Although a number of studies have drawn attention to the indigenous use of wetland resources and the importance of wetlands to human populations (Richards, 1985, 1995; Turner, 1986; Dries, 1991; Denny and Turyatunga, 1992; Adams, 1993; Roggeri, 1998), wetlands have remained under threat from overexploitation and large-scale, top-down development activities which have sought to replace these economically unattractive areas – in Western eyes – with more "productive" land uses.

Illubabor and its wetland resources

Illubabor zone in south-west Ethiopia (Figure 3.1) is one of the most fertile and least exploited regions of the country. This is largely a result of the specific environmental characteristics of the south-west highlands, particularly the dominant montane rainforest vegetation (*Aningeria adolfi-friederici*, *Croton macrostachyus*, and *Sapium ellipticum*) and the warm, temperate climate, which are atypical of conditions in the rest of the country. Mean annual temperatures in Illubabor zone average 20.7°C and rainfall is often in excess of 1,800 mm per annum (Solomon Abate, 1994). The undulating topography of the landscape, which ranges between 1,400 m and 2,000 m above sea level, combined with the climatic conditions, produces an environment characterized by steep-sided river valleys and flat, waterlogged valley bottoms. The accumulation of runoff, poor drainage, and a high groundwater table in these valley bottoms promote the formation of permanent and seasonal swamp-like headwater wetlands which range in size from less than 10 ha to more than 300 ha (Dixon, 2000). In Illubabor alone, government estimates suggest that these wetlands account for approximately 1.6 per cent (26,488 ha) of the total land area (Afework Hailu, 1998).

The wetlands of central Illubabor zone are important natural resources in terms of both their environmental functions and their products, which are used by local communities (Table 3.1). They represent a vital source of water throughout the year in an area which receives half of its annual rainfall between June and August and only 5 per cent during the dry season months of December, January, and February (Conway and Dixon, 2000). The storage and release of water from the wetlands and their peripheral springs ensure that local communities both on site and downstream have access to clean drinking water throughout the year. The abundance of water in the wetlands also supports the growth of dense

Figure 3.1 The location of Illubabor in Ethiopia

sedge vegetation known locally as *cheffe* (*Cyperus latifolius*). Local communities have traditionally harvested this *cheffe* for use as a roofing and craft material, whilst also using it throughout the year in a range of ceremonies and celebrations. In particular, *cheffe* is used as a floor covering on Easter Sunday and as such it is a marketable commodity. The wetlands also provide a habitat for a variety of other plant communities, some of which are used for medicinal purposes by wetland communities. For example, the plant known locally as *balawarante* (*Hygrophila auriculata*) is used as a treatment for various skin diseases, whilst *busuke* (unknown) is used as an enrichment in children's food (Zerihun Woldu, 1998).

As reservoirs of soil moisture during dry periods, these wetlands are

Table 3.1 Wetlands and their beneficiaries in Illubabor zone

Uses	Estimate of households benefiting (%)
Social, ceremonial use of sedges	100 (including urban dwellers)
Thatching reeds	85 (most rural households)
Sedges used for crop-guarding huts	30
Dry-season grazing	30 (most cattle owners)
Water for stock	30 (most cattle owners)
Cultivation	25
Domestic water from springs	50–100
Craft materials (palm and sedge products)	5
Medicinal plants	100 (mostly indirectly by purchase from collectors/traditional doctors)

Source: Wood *et al.*, 2002

also attractive agricultural resources and many have been used in the past, albeit on a small, informal scale, to cultivate maize much earlier in the agricultural calendar than on the uplands (Tafesse Asres, 1996; Wood, 1996). This practice, which includes the majority of the wetland maize crop being harvested before maturation, during its "green" phase, facilitates the production of crops during a period of the year normally associated with food shortages. During the last 100 years, however, it appears that wetland cultivation has extended dramatically to include larger areas of wetlands and in many cases whole wetlands have been drained and cultivated (Tafesse Asres, 1996). Currently the complete drainage and cultivation of wetlands is a common phenomenon throughout several zones in south-west Ethiopia, notably Wellega, Illubabor, and Jimma (Figure 3.1) (Afework Hailu, 1998).

The history of wetland cultivation

In most cases there is a consensus among wetland farmers that drainage and cultivation of wetlands was originally initiated in response to food shortages on the uplands caused particularly by drought, which is common even in this well-watered part of Ethiopia (Pankhurst, 1985; Dessalegn Rahmato, 1991; UNDP, 1999). In Illubabor, rather than the farmers themselves initiating wetland agriculture, however, it appears that the feudal landowners between the Menelik and Haile Selassie eras (1913–1974) and the agricultural policies of the Derg[1] regime (1974–1991) and current Federal Democratic government (1991 to the present) have had more of a direct influence on bringing wetlands into cultivation (Taye Mengistae, 1990; Alemneh Dejene, 1990). For example, farmers at one wetland in central Illubabor described how the governor of Illubabor between 1911 and 1918, Dejazmach Ganame, instructed the landlords in their district to begin cultivating wetlands as a result of food shortages throughout the zone (Tegene Sishaw, 1998).

During the Derg government wetland cultivation was encouraged in order to meet regional targets of food self-sufficiency. Furthermore, those farmers who failed to cultivate their wetland plots risked the reallocation of their land by the state to the landless or those who were willing to expand into wetland cultivation (Afework Hailu, 1998). Since 1991 the Oromiya Bureau of Agriculture has regularly instructed farmers through their wetlands task force initiatives (Afework Hailu, 1998) to cultivate wetlands to meet food production targets. Whilst wetland agriculture is clearly linked to food security in the region, several other factors have been identified as contributing to expansion of wetland agriculture (Wood, 1996; Solomon Mulugeta *et al.*, 2000). The expansion of coffee production in the area and the wider commercialization of farming in particular have resulted in local shortages of upslope agricultural land, hence the agricultural use of wetlands has become the main means of subsistence for some farmers. In addition, following the famine of 1984 Illubabor was chosen as a resettlement area for famine victims by the government. This inward migration of approximately 80,000 people, often to localized areas, resulted in further agricultural land shortages (Alemneh Dejene, 1990) and in many cases wetland plots were allocated to settlers (who, unlike the Oromo population, had no experience of farming under such conditions).

As wetland agriculture has become increasingly common among rural communities in Illubabor, there has also been some concern over its environmental sustainability. Recent reports from Illubabor suggest that a number of wetlands show severe signs of environmental degradation, characterized by a fall in water-table levels and changes in soil and vegetation (Kebede Tato, 1993; Butcher and Wood, 1995; Wood, 1996; Afework Hailu, Abbot, and Wood, 2000). Under these conditions wetlands are unable to provide their full range of functions and benefits, and this has implications for food security in the region and the availability of water to local communities, both around the wetlands themselves and downstream. In addressing these concerns, the Ethiopian Wetlands Research Programme (EWRP) recently embarked upon an extensive programme of interdisciplinary research in Illubabor zone, in which the functioning of wetlands and the motivating forces and management practices contributing to sustainable and unsustainable use were explored (Wood and Dixon, 2002).

Table 3.2 The core wetlands selected for study

	Type 1 (small headwater wetlands)	Type 2 (small mid-valley wetlands)
Pristine	Chebere	Anger (lower)
Partially cultivated	Wangeneye, Supe	Anger (lower)
Fully cultivated	Bake Chora	Dizi
Degraded	Hurumu	Anger (upper)
Regenerating	Tulube	Anger (upper)

EWRP research

One specific area of research within Illubabor focused on the role and significance of local communities and their IK in the design and implementation of wetland management practices. Investigations of wetland users' hydrological knowledge and the application of this knowledge in hydrological management strategies were regarded as critical to a wider understanding of the dynamics of wetland use and ultimately wetland sustainability throughout the area. The research used eight wetland sites, located in central Illubabor, considered to be representative in terms of their variability in land use and physical characteristics (Table 3.2) (Dixon, 2000).

A programme of meetings with farmers from each of these wetlands was established, in which a range of participatory rural appraisal (PRA) tools were employed over several sessions. Tools such as resource mapping, seasonal diagrams, transect walks, and Venn diagrams (Chambers, 1992; IIRR, 1996; Grenier, 1998), among others, were employed at each site, facilitating a high level of interaction between the research team and the wetland users (Dixon, 2000). These sessions facilitated the exchange of information on topics ranging from seasonal hydrological and vegetation changes in each wetland to the past and present sources of wetland management knowledge and techniques. In addition, a hydrological monitoring programme was undertaken to establish the seasonal hydrological characteristics of the wetlands, enabling comparisons of wetland knowledge and hydrological reality to be made.

Wetland knowledge and wetland management practices

Local wetland management practices are based upon the body of IK held by wetland communities, which is itself rooted in communities' perceptions, experiences, and understanding of wetland eco-hydrological relationships. Having focused on how wetland users perceive and apply their knowledge of the wetland system, the research findings indicated that farmers do possess an extensive and accurate understanding of the dynamics of the wetland environment, and in many ways this knowledge does form the basis of wetland management practices which can be considered sustainable (Dixon, 2000). These practices and the knowledge on which they are based are discussed below.

Hydrological knowledge and hydrological management

Wetland farmers clearly possess extensive knowledge of the wetland hydrological system, particularly the spatial and temporal dimensions of the wetland water table. Water is almost universally recognized by farmers as fundamental to the functioning and survival of wetlands, and some suggested that excessive drainage of wetlands rendered them ‘‘lifeless’’ and ‘‘just like bleeding a person to death’’ (Afework Hailu and Abbot, 1999).

Seasonal diagrams were employed to demonstrate an in-depth knowledge of the seasonal patterns of rainfall around their wetland (Figure 3.2), the seasonal variations in water-table elevation (Figure 3.3), and

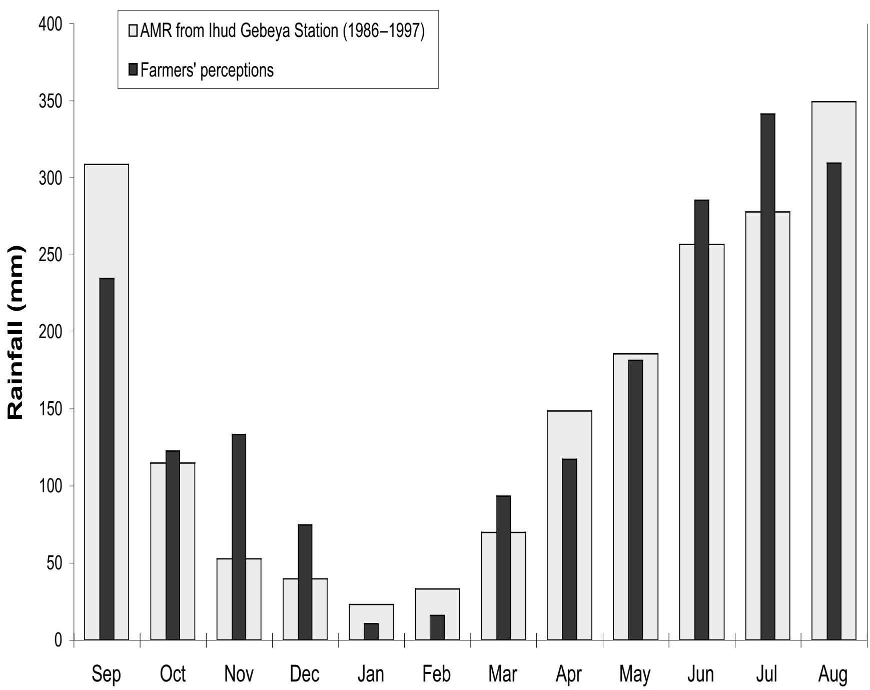

Figure 3.2 Farmers’ perceptions of rainfall in Bake Chora wetland compared to the rainfall data

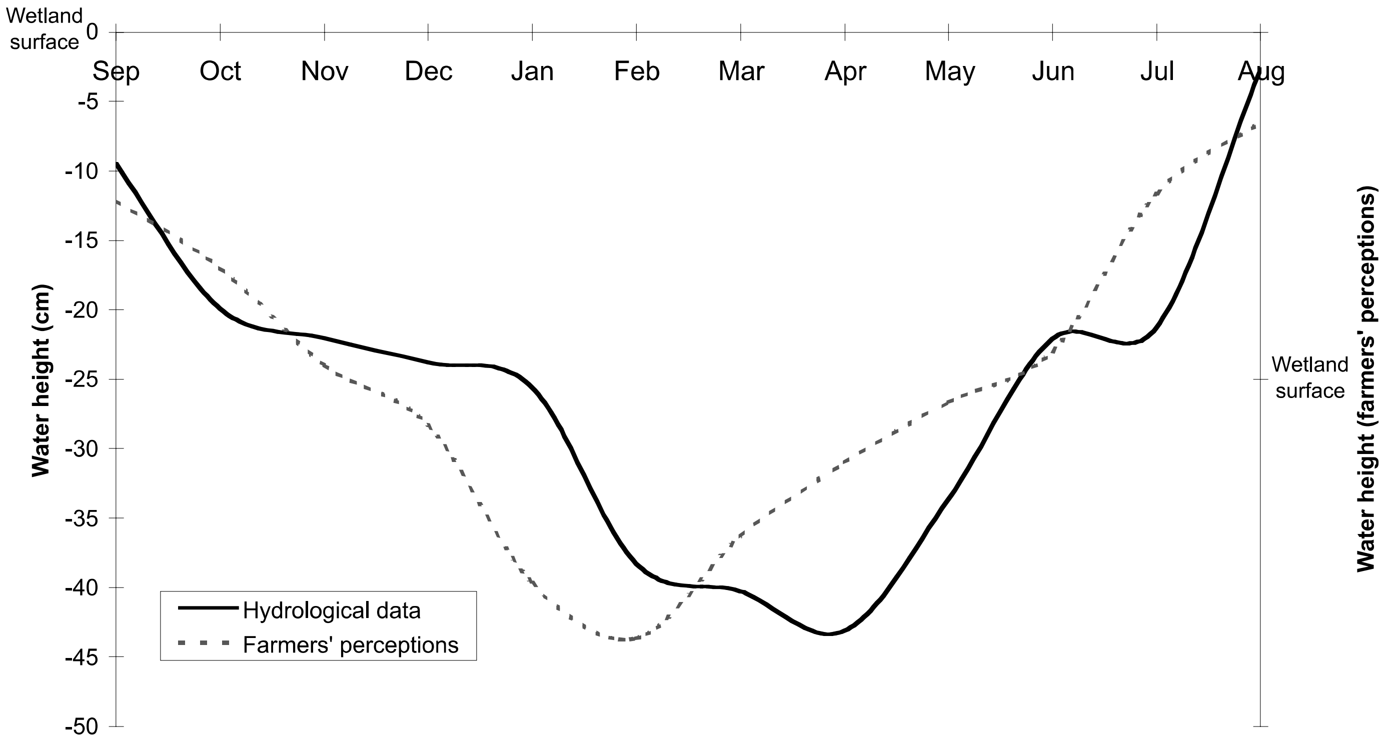

Figure 3.3 Farmers' perceptions of the water-table elevation in Bake Chora wetland compared to the hydrological data

the relationship between both. This illustrates their understanding of the storage capacity of wetland catchments and the rainfall runoff at different times of the year. The comparison between actual rainfall and perceived rainfall (Figure 3.2) indicates that whilst the perceived quantity of rainfall may differ from the actual recorded levels, farmers' knowledge of the trend in rainfall during a typical year remains accurate. Similarly, whilst farmers' perceptions of the wetland water-table height during the year appear higher than those actually measured, the seasonal trends of both are remarkably similar (Figure 3.3). Furthermore, the anomalous weather conditions (an extended dry season) during the 1997–1998 season offer some explanation for the difference between farmers' knowledge (which was indicative of average conditions) and the water-table data for that year.

Farmers were also able to elaborate on the consequences of any deviations from the normal hydrological regime, particularly the effects of flooding or drought. For example, at Supe wetland farmers pointed out that:

> Last year the rainfall in October and November was much heavier than usual. As a result, the upland crops suffered and the coffee was washed away. The wetland was also flooded but it didn't really matter because the harvest was over by then. (Supe farmer, 15 April 1998.)

In addition to their knowledge of seasonal trends, wetland farmers also demonstrated an awareness of the spatial variability of the wetland water table not just within their individual plots but throughout the wetland as a whole. According to farmers, the wetland water table is influenced by a range of factors which include variations in soil characteristics, the number and location of springs present, the presence of rocks, and different vegetation types. In the words of one farmer from Supe wetland:

> The lower part of the wetland is always wetter. When we try to drain this area we can't dig it properly. When there's excess rainfall, the bottom becomes wet first and the moisture spreads upwards towards the head of the wetland. (Supe farmer, 15 April 1998.)

Such knowledge of the characteristics and variability of the wetland hydrological system form the basis of the farmers' hydrological management activities which facilitate crop cultivation. In particular, the design and management of drainage channel depth, width, and layout each season is carried out on the basis of acquired hydrological knowledge (Dixon, 2000). The saturated anaerobic conditions present in most wetlands necessitate drainage to lower the water table beyond the root zone of the crops to be cultivated. This ensures a moisture supply without the risk of waterlogging, which would lead to the destruction of the maize crop (Acland, 1971). The excavation and maintenance of drainage channels are a critical part of the wetland farming calendar, and in most wetlands are usually carried out after the wetland maize harvest (during the peak rainfall period of June to September) in preparation for the new growing season (Figure 3.4). Although some farmers grow *tef* (*Eragrostis tef*) or vegetables on the residual moisture between September and December, the main wetland maize-growing season usually begins between December and February. For both cultivation regimes farmers agree that it is important to have the necessary drainage system in place several months prior to sowing.

Drainage systems are not haphazard in design. Most drained wetlands are characterized by the presence of a central channel which never exceeds 1 m in width and depth, although the dimensions may vary according to the gradient of the wetland or the specific water demands of wetland plots. Farmers suggest that if this central channel is deeper at the outflow of the wetland than the inflow, there will be more rapid drainage of water from the wetland. Conversely, farmers are also aware that deeper inflow and shallower outflow drainage channels can facilitate the accumulation and longer residence of water in the wetland (Dixon, Afework Hailu, and Wood, 2000). In the design and maintenance of their central drainage channel, farmers periodically apply knowledge of both these techniques in order to ensure the correct soil moisture conditions suitable for crop production.

The central channel also receives water from a number of secondary channels, which are usually laid out in a herringbone pattern. The precise location and spacing of these secondary channels are based upon the farmers' knowledge of the hydrology and topography of different areas of the wetland, with more drains being excavated where flooding is a particular problem. Although the width and depth of drainage channels tend to remain the same each year, farmers practise a system of either ditch blocking or ditch clearing in order to regulate the water input and output from different wetland plots. The practice of ditch blocking using soil or crop residues is employed prior to sowing as a means of reflooding drained wetland areas so that the soil fertility and soil structure are more conducive to crop growth. In some cases farmers may also block their drainage ditches later in the season if there is an absence of rain and the wetland soil becomes too dry. Conversely, where waterlogged conditions exist, either at the beginning of the season or as a result of heavy rain, farmers may maintain their drains by removing the invasive vegetation or sediment which hinders the flow of water through the drainage network.

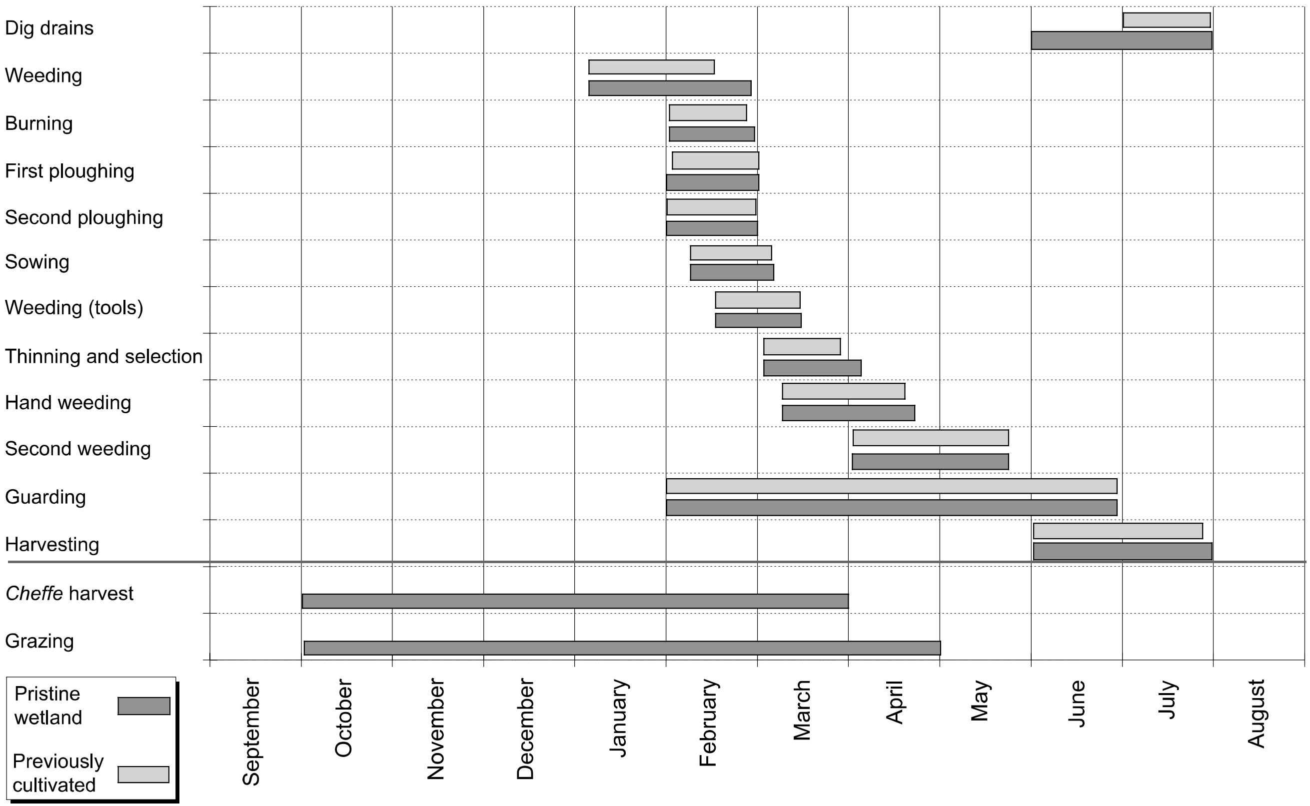

Figure 3.4 A typical seasonal calendar of wetland farming activities produced by farmers at Supe wetland

Critically, farmers related how the design of the central and secondary channels has evolved over time since their initial attempts at drainage and cultivation. Accounts of the origins of wetland drainage knowledge vary between sites, although in the *kebele* (community) of Bake Chora there is agreement that a local religious teacher was the first to disseminate wetland drainage technology to local communities in the area. Meanwhile, in other areas, farmers report that they initially held meetings amongst themselves to discuss the requirements of drainage and cultivation. In most cases, however, wetland drainage and cultivation techniques have been developed and modified through a process of trial and error involving changes to the depth, width, and location of drainage channels. As a result, knowledge of water management practices and the variable conditions in which different practices are suitable has been acquired. The farmers have progressed from the initial application of well-established upland farming practices in the wetland environment to the development of a whole new repertoire of hydrological management technologies and practices shaped by their experiences of wetland use.

Soil management practices

The multiple benefits of the effects of specific hydrological management activities on soil and vegetation are well understood by Illubabor's wetland farmers. For example, ditch blocking and the reflooding of drier wetland areas are considered to benefit the hydrological and nutrient demands of wetland cultivation. Illubabor's wetland farmers are also knowledgeable of the range of different soils found in their wetlands and the implications of these for crop production and hydrological management.

Discussions with farmers identified the existence of an indigenous system of wetland soil classification, consisting of either shallow soils or deep soils (Belay Tegene and Hunt, 2000). Shallow soils are not considered suitable for crop cultivation on account of their poor fertility and moisture retention, hence they are left uncultivated in contrast to the deeper soils. Within these groups, farmers also classify the soil as either dark (*beyo guracha*) or grey (*beyo daleti*). *Beyo guracha* is considered by farmers to be a more fertile soil which has a greater moisture-holding capacity compared to *beyo daleti*, which is associated with overcultivated soils. Where shallow *beyo guracha* soils overlay *beyo daleti* subsoils, however, farmers may avoid cultivation and instead reserve such areas for *cheffe* regeneration. In addition, farmers recognize the existence of red soil (*beyo dima*) which dominates the upslope areas. This is considered less fertile than *beyo guracha*, yet its occurrence in wetlands is also regarded as beneficial to the growth of *cheffe*.

Although farmers acknowledge that repeated drainage and cultivation can cause the conversion of *beyo guracha* to *beyo daleti*, resulting in lower crop yields, they are also aware that the fertility of the soils is constantly being improved by the input of sediment from the catchment via runoff and flooding. Having understood the principles behind soil fertility restoration, farmers have developed their own management practices which build upon and enhance these natural processes. As outlined above, a system of ditch blocking has been developed which regulates the water table and the supply of soil nutrients as a result of the retention of catchment runoff. In addition, rather than clearing crop residue from their wetland plots, many farmers leave this material on their fields and use ditch blocking as a means of influencing the course of decomposition of this plant material, thereby improving soil fertility. In contrast, some farmers prefer to burn their crop residue and plough the ashes into the soil. The grazing of cattle in the wetlands is also regarded as an important means of providing a nutrient input, although farmers are equally aware that heavy grazing may lead to soil compaction, erosion, and the destruction of natural vegetation. In most cases, farmers prohibit grazing in cultivated wetlands because of the threat of degradation. In Bake Chora wetland in particular, where wetland agriculture has been sustained for over 80 years with little sign of degradation, cattle are not allowed access to the wetland even after the harvesting of crops.

Wetland vegetation management

As with the hydrological regime and the wetland soil characteristics, farmers also possess intimate knowledge of the dynamics of wetland vegetation and this knowledge is applied in a variety of management practices (Afework Hailu, Abbot, and Wood, 2000; Dixon, 2000). The relationship between *cheffe* and the wetland water table is well understood by farmers, who regard *cheffe* as both a hindrance to effective drainage and cultivation and a means of wetland regeneration. The growth of *cheffe* is associated with waterlogged conditions and its presence is used by farmers as an indicator of the return of natural wetland characteristics following drainage. Farmers also use a range of other wetland plants as indicators of the state of their wetland. For example, the plants known locally as *inchinne* (*Triumfetta pilosa*) and *tuffo guracha* (*Asteraceae*) are indicators of good soil fertility. In addition, wetlands with deep green *cheffe* are associated with fertile, dark soils which are suitable for agricultural use. *Kemete* (*leersia hexandra*) and *kello* (unknown), meanwhile, are considered indicators of poor fertility and rapidly colonize those wetlands which have been cultivated for a number of years and are suffering from nutrient deficiencies (Dixon, 2000; Zerihun Woldu, 2000).

Knowledge of these changes in wetland vegetation has enabled farmers to develop fallowing systems in which wetland plots are abandoned when plants such as *kemete* start to invade and crop yields decline. Plots may remain uncultivated until the vegetation starts to include indicators of increasing fertility such as *inchinne*, or when *cheffe* recolonizes and the wetland water table starts to regain its natural characteristics. Where *kemete* and *kello* dominate the wetland many farmers prefer to burn this vegetation and then flood the wetland, which encourages the recolonization of *cheffe*. Some farmers have incorporated areas reserved for *cheffe* vegetation into their wetland management strategies as a result of its association with waterlogged soils. These act as a reservoir of soil moisture throughout the year. *Cheffe* is also a vital resource in itself for local communities who use it for roofing and craft material, although it is widely recognized that use of *cheffe* in its first year of regeneration should be avoided on account of its poor quality. Many communities have also reserved their whole wetland specifically for *cheffe*, which is regarded as more valuable than the equivalent crop production from a similar wetland area under cultivation.

Applying IK towards sustainable wetland management

On the evidence presented in the preceding sections, the wetland users of central Illubabor zone clearly possess extensive knowledge of the local wetland eco-hydrology, which offers a sound basis for sustainable wetland management strategies. Furthermore, their wetland management does appear to be sustainable in some respects, in that the environmental impacts of wetland use tend to be balanced with farmers' management abilities. Of the eight sites studied during this research, indications of permanent environmental degradation were relatively scarce and even the "degraded" site of Hurumu showed some signs of regeneration with the return of *cheffe* vegetation and a recovering water table (Dixon, 2000). Whilst the research findings do not necessarily contradict the initial reports of widespread wetland degradation in Illubabor (examples of severely degraded sites were reported elsewhere in Illubabor zone: Afework Hailu, Abbot, and Wood, 2000), the general indication is that wetland farming knowledge and practice are more developed and able to cope with change than previously envisaged. For example, whilst many farmers have the opportunity to double crop their wetland, first with *tef* and then with maize, they also recognize that the cultivation of *tef* can induce problems of soil fertility and a fall in the water table, which has consequences for maize cultivation (Afework Hailu, Abbot, and Wood, 2000). Wetland management in its present form can, therefore, be considered hydrologically sustainable in that where drainage and cultivation are being undertaken the hydrological characteristics of the wetland remain similar from year to year, sustaining the range of functions and benefits which depend on it (Dixon, 2000).

Although this state of hydrological sustainability is facilitating crop production without degradation in the wetlands, the situation in many of the wetlands throughout the area is one where crop production does not actually meet the needs of the farmers. Whilst most farmers who were spoken to possess knowledge of practices and technologies which could sustain crop production at a higher level than that currently achieved, the farmers also recognize that there is a problem of operationalizing and applying their knowledge to fulfil their management aims. The application of wetland knowledge, it seems, is restricted by a range of constraints with which farmers have to contend. Although diverse, the most common constraints recalled by farmers included the climatic uncertainty which has prevailed in recent years, the actual geomorphological constraints in the wetlands themselves (e.g. rock outcrops), and the farmers' own individual socio-economic situation (Dixon, 2000).

In citing climatic uncertainty as a problem, farmers referred to the unpredictability of the weather in recent years, particularly the extension of the dry season by approximately one month and a more severe and extended rainy season. Consequently many of the activities within the wetland farming calendar, such as the clearing of ditch vegetation to maintain drainage, are no longer ideally adapted to the perceived long-term seasonal trends in wetland hydrology. Although farmers are aware of the impacts of climate change and they could carry out practices such as ditch blocking where and when required, they are constrained by time and resources available to them. Geomorphological constraints such as rocks or the topography of the wetlands pose a persistent problem to farmers in terms of hydrological variability. These, together with the unpredictability of the climate (UNDP, 1999), produce a wide range of possible hydrological scenarios both spatially and temporally, rendering adaptation of the whole wetland for agricultural production virtually impossible. The most influential factor affecting the management of wetlands is, however, the farmer's socio-economic situation. Essentially, the wealth and resources of each farmer determine the extent to which they utilize the wetlands for food production or natural products, and also the ways in which they use the wetland (Afework Hailu, 1998; Tegene Sishaw, 1998; Solomon Mulugeta *et al.*, 2000). Whilst wealthy farmers can afford the benefits of cattle, labour, and farming equipment, poorer farmers may have insufficient resources to cultivate their wetland plots (usually in addition to upland plots). The need for natural wetland products also differs between the rich and poor, e.g. poorer farmers require *cheffe* for the roofs of their houses whilst richer farmers may afford the luxury of corrugated iron.

Whilst these constraints directly affect the ways in which farmers are able to apply their existing wetland knowledge, there is a wider issue of whether farmers possess the capacity to adapt to these constraints through the acquisition and evolution of new knowledge and practices. Under circumstances where farmer cooperation, communication, and the opportunities for innovation are plentiful, wetland management arguably has a greater potential to be both successful and sustainable. Hence this indigenous capacity, characterized by a dynamic and evolving indigenous knowledge system, can be considered a prerequisite to the evolution of wetland management practices and consequently sustainable wetland management itself.

Although it is recognized that there have been some changes to the ways in which wetlands are managed since drainage and cultivation were initiated, discussions with farmers at the various study wetlands revealed that examples of innovation and the communication of wetland knowledge between farmers and between different wetland communities were relatively rare (Dixon, 2000). In effect, the mechanisms through which new knowledge is acquired and wetland management practices evolve generally appear underdeveloped or underutilized. With respect to the communication of wetland management knowledge and information, most farmers suggested that they had little contact with those outside their immediate wetland community, including other farmers and government agricultural extension agents. In contrast, farmers did acknowledge that within their own communities there exists some shared responsibility for wetland management and that knowledge is exchanged between community members:

> We talk together [about wetlands] because if your neighbour can't cultivate his wetland plot, then there will be a problem with your yield. The problem is that if your neighbour doesn't drain, there will be a build-up of water on your land so it will be impossible to plough. If one farmer makes a small drain, then the drainage won't work – it depends on the level of the land. We have to get together, discuss it, and get it right. (Tulube farmer, 6 April 1998.)

The research found little evidence to suggest that the wetland communities engage in more formal types of experimentation and adaptation, characterized, for example, by on-farm trials or curiosity experiments (Johnson, 1972; Millar, 1993; Rhoades and Bebbington, 1995; McCorkle and McClure, 1995). Instead, the adaptation and evolution of the wetland management system have been characterized by a more gradual, inconspicuous process of trial and error occurring over several generations.

Minor modifications to existing practices, made in response to environmental changes rather than sudden leaps in wetland technology, appear to have been the norm. Critically, such adaptive responses tend to be carried out in the following season rather than during the event itself, hence farmers are never able to adapt fully their management practices to a changing wetland environment.

In summary, whilst wetland management in the areas studied appears to be environmentally sustainable, the non-application of wetland knowledge and the inability of farmers' wetland knowledge system to adapt to various constraints indicate that wetland management cannot be considered wholly sustainable. A critical component of sustainable wetland management is the capacity of wetland users to develop sustainable management practices in the face of environmental or socio-economic change, and on the basis of the research findings there is some doubt over whether this would occur in Illubabor in the future. Several researchers have suggested that one of the main limitations to IK is its inability to cope with rapid environmental or socio-economic change (Farrington and Martin, 1988; McCorkle, 1989; Wood, 1991; World Bank, 1998), and certainly whilst the wetland knowledge system in its current state may support environmentally sustainable wetland use, undoubtedly the social and environmental circumstances under which wetland use is being undertaken in Illubabor are beginning to change. Climatic unpredictability is clearly causing problems for farmers, but, in addition, regional government policy is having a direct impact through wetlands task force directives which, since 1999, have required farmers throughout the zone to bring previously uncultivated areas of wetland into production in order to address widespread food shortages in the zone (UNDP, 1999). With more and more demands being placed on wetland users to increase agricultural output both in the wetlands and in upslope farming systems, it is possible that farmers will have even less time and resources available to develop and adapt their wetland management practices to meet these new demands. As a result there is a real risk of wetland resources being overexploited in the short term, which could induce long-term environmental degradation and unsustainable wetland use.

Empowering indigenous knowledge

If the range of benefits from these wetlands are to be sustained at the present time and for the future, there is a need for wetland farmers to develop new management practices which can cope with a range of problems and facilitate the successful, sustainable, and equitable production of wetland benefits. This can be achieved in two ways:

- farmers can receive external technical assistance on particular wetland management practices
- farmers can develop, in an endogenous manner, solutions to their problems.

Whilst the former may represent a solution in the short term, it is itself an unsustainable approach. Alternatively, if farmers are given the opportunity to develop their own solutions, they also develop their indigenous wetland knowledge and add to their social capital, creating a pool of knowledge which can be used and applied where necessary in the future.

Figure 3.5 suggests a framework for empowering indigenous wetland knowledge so that farmers' capacity to adapt their wetland management practices to environmental and socio-economic changes can be strengthened. The first stage would involve a recognition of the strengths and weaknesses of the current wetland knowledge system. Here there is a role to play for an external agent in bringing together the wetland community and facilitating an arena in which various members can assess their own knowledge. Key issues to be addressed could include the opportunities for knowledge exchange within the community and with other wetland communities or rural institutions. IK research has also demonstrated that knowledge is not shared equally among rural communities; hence there may be a need to recognize specific individuals who possess specialized knowledge and could be sources of ideas or key innovations and adaptations that have taken place and which should be disseminated to benefit the wider community.

Throughout a participatory process involving external agents and wetland community members, emphasis should be placed on assisting the local community to organize their own wetland knowledge resources in a way which can promote the evolution of wetland knowledge. Recent initiatives by the EWRP which brought farmers from different communities together in a series of workshops and site visits have facilitated such an exchange of wetland knowledge, with farmers themselves claiming that they had acquired new knowledge as a result of interaction with their fellow farmers.

Once the indigenous wetland knowledge network and the adaptive capacity of farmers have been strengthened, attention can then turn towards the second stage and specific wetland management problems. The continuing process of equitable participation between the wetland stakeholders and external agents provides an opportunity to exchange different knowledge of wetlands so that management practice experiments

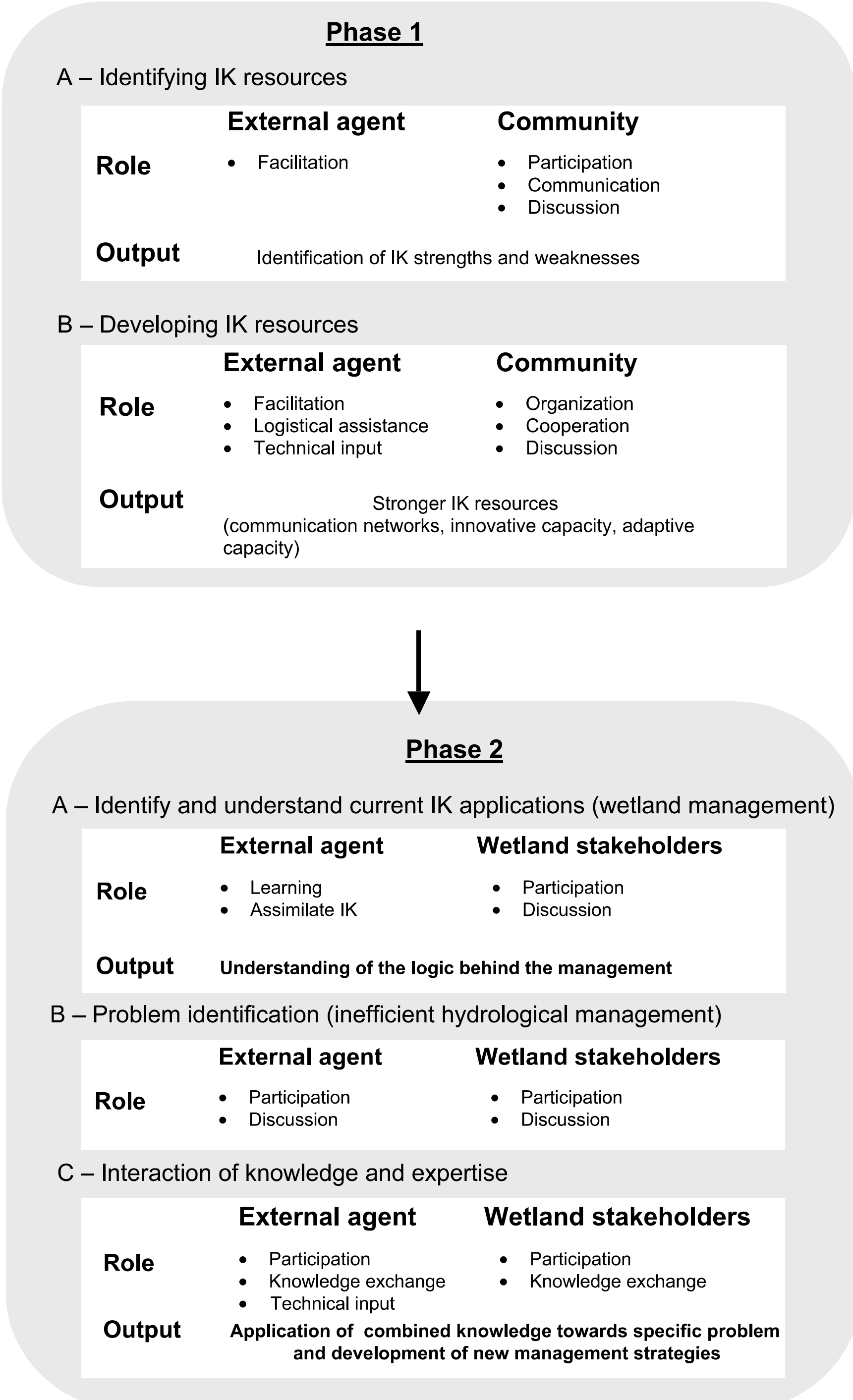

Figure 3.5 A framework for empowering indigenous wetland knowledge

can be developed in the light of a wider understanding of their benefits and consequences.

Conclusions

Indigenous management practices and technologies, the knowledge on which these are based, and the dynamics of the wetland knowledge system all play a critical role in the sustainable management of Illubabor's wetlands. As a result of the accumulation and development of wetland knowledge and experiences by farmers, many wetlands in Illubabor are being managed in a sustainable manner through the application of a range of indigenous technologies and practices. Although examples of degraded wetlands do exist, these appear to be less ubiquitous than originally envisaged at the onset of the research activity in this area. A main concern, however, is that the farmers' indigenous wetland knowledge system may struggle to cope with any future environmental or socio-economic changes, particularly as the adaptation and evolution of wetland knowledge and practices appear relatively slow, and the pressures to use wetlands more intensively increase. Although in Illubabor climatic change may be influential in this respect, the ability of indigenous wetland knowledge to contribute to sustainable wetland management appears more dependent upon the socio-political and economic climate in which it functions. In Illubabor, wetland communities have been increasingly influenced or constrained by the resources available to them and the top-down prescriptive policies of agricultural extension. At a political level, a situation where land remains the property of the state and access rights are unclear offers little incentive for farmers to invest the resources and knowledge they have in long-term management strategies. Under such circumstances it may be hazardous to rely completely on local communities' IK to continue to manage wetlands in a sustainable manner.

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Notes

1. The term "Derg" refers to the government of Ethiopia between 1974 and 1991, in which power was initially shared by a military committee and later centralized into the hands of President Mengistu Haile Mariam.

REFERENCES

Acland, J. D. 1971. *East African Crops*. London: Longman.

Adams, W. M. 1993. "Indigenous use of wetlands and sustainable development in West Africa", *Geographical Journal*, Vol. 159, No. 2, pp. 209–218.

Afework Hailu. 1998. *An Overview of Wetland Use in Illubabor Zone, South-west Ethiopia*. Metu and Huddersfield: EWRP/University of Huddersfield.

Afework Hailu and P. G. Abbot. 1999. *Report on the First Farmers to Farmers Demonstration in Dire Wetland, Jenete Shennie, Bake Chora Kebele, Illubabor Zone*. Metu and Huddersfield: EWRP/University of Huddersfield.

Afework Hailu, P. G. Abbot, and A. P. Wood. 2000. "Appropriate techniques for sustainable wetland management", Report for Objective 4. Metu and Huddersfield: EWRP/University of Huddersfield.

Agrawal, A. 1995. "Dismantling the divide between indigenous and scientific knowledge", *Development and Change*, Vol. 26, No. 3, pp. 413–439.

Alemneh Dejene. 1990. *Environment, Famine and Politics in Ethiopia: A View from the Village.* Boulder, CO, and London: Lynne Reinner.

Barbier, E. B. 1993. "Sustainable use of wetlands – Valuing tropical wetland benefits: Economic methodologies and applications", *Geographical Journal*, Vol. 159, No. 1, pp. 22–32.

Barbier, E. B., M. Acreman, and D. Knowler. 1997. *Economic Valuation of Wetlands: A Guide for Policy-makers and Planners*. Gland: Ramsar Convention Bureau.

Belay Tegene and C. O. Hunt. 2000. "The characteristics and management of wetland soils of Metu Wereda, Illubabor zone of Oromia region", Report 2 for Objective 2. Metu and Huddersfield: EWRP/University of Huddersfield.

Butcher, D. P. and A. P. Wood. 1995. *Sustainable Wetland Development in Highland Illubabor: A Preliminary Review of the Experience of Menschen Fur Menschen*. Huddersfield: Department of Geographical and Environmental Sciences, University of Huddersfield.

Chambers, R. 1983. *Rural Development: Putting the Last First*. London: Longman.

Chambers, R. 1992. "Rural appraisal: Rapid, relaxed and participatory", IDS Discussion Paper No. 311. Brighton: IDS.

Chambers, R., A. Pacey, and L. A. Thrupp (eds). 1989. *Farmer First: Farmer Innovation and Agricultural Research*. London: Intermediate Technology Publications.

Claridge, G. and B. O. Callaghan. 1997. *Community Participation in Wetland Management: Lessons from the Field*, Proceedings of Workshop 3 of the International Conference on Wetlands and Development, Kuala Lumpur, 9–13 October 1995. Dordrecht: Wetlands International.

Conway, D. and A. B. Dixon. 2000. ''The hydrology of wetlands in Illubabor zone'', Report 1 for Objective 3. Metu and Huddersfield: EWRP/University of Huddersfield.

Davis, T. 1993. *Towards the Wise Use of Wetlands*, Report of the Ramsar Convention Wise Project. Gland: Ramsar Convention Bureau.

Denny, P. 1994. ''Biodiversity and wetlands'', *Wetlands Ecology and Management*, Vol. 3, No. 1, pp. 55–61.

Denny, P. and F. Turyatunga. 1992. ''Ugandan wetlands and their management'', in E. Maltby, P. J. Dugan, and J. C. Lefeuvre (eds) *Conservation and Development: The Sustainable Use of Wetland Resources*, Proceedings of the Third International Wetlands Conference, Rennes, France, 19–23 September. Gland: IUCN, pp. 77–84.

Dessalegn Rahmato. 1991. *Famine and Survival Strategies: A Case Study from North-east Ethiopia*. Uppsala: Scandanavian Institute of African Studies.

De Walt, B. 1994. ''Using indigenous knowledge to improve agriculture and natural resource management'', *Human Organisation*, Vol. 53, No. 2, pp. 123–131.

Dixon, A. B. 2000. ''Indigenous knowledge and the hydrological management of wetlands in Illubabor. Ethiopia'', PhD thesis, University of Huddersfield.

Dixon, A. B., Afework Hailu, and A. P. Wood. 2000. ''Sustainable wetland management in Illubabor zone: The role of indigenous technologies'', paper presented at the Second National Seminar on Sustainable Development and Appropriate Technology, Bahar Dar University, 10–11 November.

Dries, I. 1991. ''Development of wetlands in Sierra Leone: Farmers' rationality opposed to government policy'', *Landscape and Urban Planning*, Vol. 20, No. 2, pp. 223–229.

Dugan, P. J. 1990. *Wetland Conservation: A Review of Current Issues and Action*. Gland: IUCN.

Farrington, J. and A. Martin. 1988. ''Farmer participation in agricultural research: A review of concepts and practices'', Agricultural Administration Unit Occasional Paper 9. London: ODI.

Fielding, D. and K. Kirsopp-Reed. 1994. ''Indigenous knowledge: The way forwards or backwards in tropical agricultural development?'', *Science, Technology and Development*, Vol. 12, Nos 2/3, pp. 134–145.

Grenier, L. 1998. *Working with Indigenous Knowledge: A Guide for Researchers*. Ottawa: IDRC.

Haverkort, B. and W. Hiemstra (eds). 1999. *Food for Thought: Ancient Visions and New Experiments of Rural People*. London: Zed Books.

Hollis, G. E. 1990. ''Environmental impacts of development on wetlands in arid and semi-arid lands'', *Hydrological Sciences Journal*, Vol. 35, No. 4, pp. 411–428.

IIRR. 1996. *Recording and Using Indigenous Knowledge: A Manual*. Cavite: International Institute of Rural Reconstruction.

Johnson, A. 1972. ''Individuality and experimentation in traditional agriculture'', *Human Ecology*, Vol. 1, No. 2, pp. 149–159.

Kebede Tato. 1993. *Evaluation of the Environmental Components of the Menschen fur Menschen Projects in Ethiopia*. Addis Ababa: MFM.

Lema, A. J. 1996. ''Cultivating the valleys: Vinyungu farming in Tanzania'', in C. Reij, I. Scoones, and C. Toulmin (eds) *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa*. London: Earthscan, pp. 139–144.

Marchand, M. and H. A. Udo (eds). 1989. *The People's Role in Wetland Management, Proceedings of the International Conference in Leiden, The Netherlands, 5–8 June 1989*. Leiden: Centre for Environmental Studies, Leiden University.

McCann, J. 1995. *People of the Plow: An Agricultural History of Ethiopia 1800–1990*. Wisconsin: University of Wisconsin Press.

McCorkle, C. M. 1989. ''Towards a knowledge of local knowledge and its importance for agricultural RD and E'', *Agriculture and Human Values*, Vol. 6, No. 3, pp. 4–12.

McCorkle, C. M. and G. D. McClure. 1995. ''Farmer know-how and communication for technology transfer: CTTA in Niger'', in M. D. Warren, L. J. Slikkerveer, and D. Brokensha (eds) *The Cultural Dimension of Development: Indigenous Knowledge Systems*. London: Intermediate Technology Publications, pp. 323–332.

Millar, D. 1993. ''Farmer experimentation and the cosmovision paradigm'', in W. deBoef, K. Amanor, K. Wellard, and A. Bebbington (eds) *Cultivating Knowledge: Genetic Diversity, Farmer Experimentation and Crop Research*. London: Intermediate Technology Publications, pp. 44–50.

Mitsch, W. L. (ed.). 1994. *Global Wetlands: Old World and New*. Amsterdam: Elsevier.

Mundy, P. A. and J. L. Compton. 1995. ''Indigenous communication and indigenous knowledge'', in M. D. Warren, L. J. Slikkerveer, and D. Brokensha (eds) *The Cultural Dimension of Development: Indigenous Knowledge Systems*. London: Intermediate Technology Publications, pp. 112–123.

Pankhurst, R. 1985. *The History of Famine and Epidemics in Ethiopia Prior to the Twentieth Century*. Addis Ababa: RRC.

Rajasekaran, B. 1993. ''A framework for incorporating indigenous knowledge systems into agricultural research, extension and NGOs for sustainable agricultural development'', Studies in Technology and Social Change No. 21. Ames, IA: Technology and Social Change Programme, Iowa State University.

Ramsar Convention Bureau. 2000a. *Establishing and Strengthening Local Communities' and Indigenous People's Participation in the Management of Wetlands*, Ramsar Handbook No. 5. Gland: Ramsar.

Ramsar Convention Bureau. 2000b. *Wise Use of Wetlands*, Ramsar Handbook No. 1. Gland: Ramsar.

Rhoades, R. E. and A. Bebbington. 1995. ''Farmers who experiment: An untapped resource for agricultural research and development'', in M. D. Warren, L. J. Slikkerveer, and D. Brokensha (eds) *The Cultural Dimension of Develop-*

ment: Indigenous Knowledge Systems. London: Intermediate Technology Publications, pp. 296–307.

Richards, P. 1985. *Indigenous Agricultural Revolution: Ecology and Food Production in West Africa*. London: Hutchinson.

Richards, P. 1995. ''The versatility of the poor: Indigenous wetland management systems in Sierra Leone'', *Geojournal*, Vol. 35, No. 2, pp. 197–203.

Roggeri, H. 1998. *Tropical Freshwater Wetlands: A Guide to Current Knowledge and Sustainable Management*, Dordrecht: Kluwer Academic Publishers.

Scoones, I. 1990. ''Wetlands in drylands: Key resources for agricultural and pastoral development in Africa'', *Ambio*, Vol. 20, No. 8, pp. 366–371.

Scoones, I. and J. Thompson (eds). 1994. *Beyond Farmer First: Rural People's Knowledge, Agricultural Research and Extension Practice*. London: Intermediate Technology Publications.

Solomon Abate. 1994. ''Land use dynamics, soil degradation and potential for sustainable use in Metu area, Illubabor region, Ethiopia'', African Studies Series A13. Berne: University of Berne.

Solomon Mulugeta, P. G. Abbot, Tegene Sishaw, and Afework Hailu. 2000. ''Socio-economic determinants of wetland use in the Metu and Yayu Hurumu weredas of Illubabor'', Report 1 for Objective 3. Metu and Huddersfield: EWRP/University of Huddersfield.

Tafesse Asres. 1996. ''Agro-ecological zones of south-west Ethiopia'', MSc thesis, University of Trier.

Taye Mengistae. 1990. ''Urban-rural relations in agrarian change: An historical overview'', in S. Pausewang, Fantu Cheru, S. Brune, and Eshetu Chole (eds) *Ethiopia: Options for Rural Development*. London: Zed Books, pp. 30–37.

Tegegne Sishaw. 1998. ''Socio-economic aspects of land use change and wetland utilisation in two communities in Illubabor zone'', MSc thesis, University of Addis Ababa.

Turner, B. 1986. ''The importance of dambos in African agriculture'', *Land Use Policy*, Vol. 3, No. 4, pp. 343–347.

Turner, R. K. 1991. ''Economics and wetland management'', *Ambio*, Vol. 20, No. 2, pp. 59–63.

UNDP. 1999. *Prosperity Fades: Jimma and Illubabor Zones of Oromia Region*, Emergency Unit for Ethiopia Assessment Mission. Addis Ababa: EUE.

Warren, D. M. 1991. ''Using indigenous knowledge in agricultural development'', World Bank Discussion Paper 127. Washington, DC: World Bank.

Warren, D. M. and K. Cashman. 1988. *Indigenous Knowledge for Sustainable Agriculture and Rural Development*, Gatekeeper Series No. 10. London: International Institute for Environment and Development.

Warren, M. D., L. J. Slikkerveer, and D. Brokensha (eds). 1995. *The Cultural Dimension of Development: Indigenous Knowledge Systems*. London: Intermediate Technology Publications.

Winarto, Y. T. 1994. ''Encouraging knowledge exchange: Integrated pest management in Indonesia'', in I. Scoones and J. Thompson (eds) *Beyond Farmer First: Rural People's Knowledge, Agricultural Research and Extension Practice*. London: Intermediate Technology Publications, pp. 150–155.

Wood, A. P. 1991. ''Beyond land use planning: Towards a participatory approach to land use planning and husbandry development for improved natural resource use'', in A. P. Wood and P. Ryden (eds) *The IUCN Sahel Studies 1991*. Gland: IUCN, pp. 113–126.

Wood, A. P. 1996. ''Wetland drainage and management in south-west Ethiopia: Some environmental experiences of an NGO'', in A. Reenburg, H. S. Marcusen, and I. Nielsen (eds) *The Sahel Workshop 1996*. Copenhagen: Institute of Geography, University of Copenhagen, pp. 119–136.

Wood, A. P. and A. B. Dixon (eds). 2002. *Sustainable Wetland Management in Illubabor Zone: Research Report Summaries*. Huddersfield: University of Huddersfield and Wetland Action.

World Bank. 1998. *Indigenous Knowledge for Development: A Framework for Action*. Washington, DC: World Bank, Knowledge and Learning Centre, Africa Region.

Zerihun Woldu. 1998. *Annual Biodiversity Report 1997–1998*. Metu and Huddersfield: EWRP/University of Huddersfield.

Zerihun Woldu. 2000. ''Plant biodiversity in the wetlands of Illubabor zone'', Report 3 for Objective 2. Metu and Huddersfield: EWRP/University of Huddersfield.

4

Sustainable management of headwater resources: Interface drainage analysis of a water divide

R. Y. Singh

Introduction

The African proverb "The earth is not ours, it is a treasure we hold in trust for our children and their children" summarizes the sustainability concept in short. Thomas Mann (*Man and His Dog*, quoted in Chorley, 1969) describes in a nutshell the vital significance of water:

> Who would not choose to follow the sound of running water? Its attraction for the normal man is of a natural sympathetic sort. For man is water's child, nine-tenths of our body consists of it and at a certain stage the foetus possesses gills. For my part I freely admit that the sight of water in whatever form or shape is my most lively and immediate form of natural enjoyment: yes, I would even say that only in contemplation of it do I achieve true self-forgetfulness and feel my own limited individuality merge into the universal.

Chorley (1969: 3) makes the point:

> We may be reminded of the fact that in the development of water as a focus of geographical interest the evolution of a human-oriented physical geography and an environmentally sensitive human geography closely related to resource management is well under way.

Emphasizing water as a focus of geographical interest, Chorley (1969: 3) states that:

Not only is it a commodity which is directly used by man but it is often the mainspring for extensive economic development, commonly an essential element in man's aesthetic experience, and always a major formative factor of the physical and biological environment which provides the stage for his activities.

Finally Chorley (1969: 6) opines that:

Geographers freed from the traditional distinction between human and physical geography and with their special sensitivity towards water, earth and man, have in these both opportunity and challenge.

It would not be out of place to mention that the mountain chapter (Chapter 13) in UNCED Agenda 21 rightly tried to celebrate the International Year of the Mountains 2002 by stating that "As a major ecosystem representing the complex and interrelated ecology of our planet, mountain environments are essential to the survival of the global ecosystem" (see also Bruno Messerli, IGU past president: Messerli, 2001). It is good news that many organizations like the UN Framework Convention on Climate Change (FCCC), the Intergovernmental Panel on Climate Change (IPCC), the UN Convention on Biological Diversity (DIVERSITAS), and the UN Convention to Combat Desertification are working at various levels. Fortunately the Mountain Research Initiative (MRI) has started working at the Swiss Academy of Sciences in Berne, and will coordinate all mountain projects in the IGBP and IHDP programmes (Messerli, 2001).

With this perspective we turn to sustainable management of headwater resources and an interface drainage analysis of a divide. These divides or watersheds in the form of mountains, ranges, ridges, spurs, and higher plateaux separate drainage basins of various orders of streams. The main topic envisages analysis using a multidisciplinary approach which leads to the study of climate, hydrology, geochemistry, geomorphology, ecology, and anthropological aspects of the basin headwater area concerned. Further, it needs a comprehensive study of cost-effectiveness of resources, which helps in planning for sustainable management. The aim of the present chapter is to highlight the morphometric analysis of geomorphic units in part of the Deccan Trap in India, with the Vindhyan Plateau divide as the study area. It is confined to stream drainage analysis, based particularly on the works of Horton (1945) and Strahler (1957).

Coming to the first part of the chapter title, "sustainable"[1] refers to continuity of renewal, restoration, or replenishment of support management of headwater resources, keeping in perspective the concept of sustainability which deals with structural, institutional arrangements which ensure that sustainable utilization actually takes place.

"Interface" refers to the interaction/interrelationship between processes pertaining to the hydrological cycle, headwater resources management, and drainage basin analysis. The chapter may digress a bit to take the environmental perspective in view. Environmental management draws on concepts developed in cultural and humanistic geography. It covers a wide range of goals related to the actions of humans to manage their activities so as to optimize benefits and minimize environmental costs. It can also be defined as "a set of applied activities designed to manage relationships in the environment and particularly those which arise from problematic interventions of humans" (Davies, 2001: 3). According to Fuggle and Rabie (1999: 3), "when management skills and techniques are applied to care for the earth ... we are dealing with environmental management. Resource management is considered in terms of the carrying capacity of the physical environment as well as in terms of the dynamics of human human-environment relations. Hydrology, however, includes both the aspects of both demand side and supply side."

It is now generally accepted that hydrological studies should be carried out within the framework of integrated catchment management, involving hydrologists, social and economic scientists, ecologists, climatologists, and water resource engineers. The concept of environmental sustainability, however, has led to the need to define that proportion of a river's natural streamflow regime that is required to maintain some level of ecological functioning (the ecological "reserve"). This has led to a multidisciplinary approach to research and practice in the field of instream flow requirement (IFR) determinations (King, Tharme, and de Villiers, 2000: 142).

The availability of modern computer hardware and software tools (GIS, modular and object-oriented programming languages, relational database tools, etc.) has removed many of the earlier restrictions that hydrologists were faced with when designing models. Hydro-SIG Java, newly introduced, will open new vistas. Linked to GIS are global/geographical positioning systems (GPS) that have become increasingly important in biogeographical studies. The use of correct statistical analysis is essential in analysing GIS data and developing models for environmental purposes, and it is often useful to incorporate multivariate statistic packages in GIS to analyse several parameters at once and evaluate any relationships that emerge. GIS can also be used in mapping of biodiversity.

It is important that models of different types are linked together to provide an integrated set of tools for hydrological and water resource problem-solving. As models and any other hydrological tools become increasingly sophisticated it becomes important for them to be supported by training and technical support programmes. Hughes (2002: 143) rightly observes that requirements for the development of hydrology are integration of research and practice, of skills and expertise (multidisciplinary approaches), within the region (regional cooperation), of individual tools and estimation methods, and of surface and water.

Geographers who have taken the ecosystem concept as their central theme in biogeography have attempted to develop an applied biogeography aimed at sustainable management of biological resources. The human species is an integral element, but one that frequently disturbs ecosystem processes to the point of no return. "James Lovelock's (1979) Gaia hypothesis postulates the total integration of the human species, along with all others, into global processes in a holistic way" (Meadows and Hill, 2002: 123).

Water resources management can be visualized in terms of an interrelating complex of functions that constitute a system. Water resources management is, however, only one such system, and the bonds which unite its component functions are complemented by the links between it and other rural and urban resource management systems, each of which in turn is composed of interconnecting multipurpose functions. Regional development plans are often designed to coordinate such a complex of resource management projects (Chorley, 1969: 566).

A water resource system is thus an integrated complex of interlinked hydrologic and socio-economic variables operating together within a well-defined area, commonly a drainage basin unit.

The present study

The study area (Manpur and environs, Madhya Pradesh, India) lies between latitudes 22° 20′ N and 22° 30′ N and longitudes 72° 35′ E and 75° 44′ E, covering an area of slightly over 361 km^2. It shares most of the south-western portion of Mhow Tahsil and a small portion of the northern part of Barwaha Tahsil in Indore and West Nimar districts respectively in Madhya Pradesh state of India. The area represents neither complexity nor variation in geological rock formations. The geological history, pregnant with geomorphological problems, is almost hidden behind the basaltic overflows, which range from the Middle Paleocene (62.5 million years ago) to the Lower Eocene (50.8 million years ago) (Singh, 1979: 100).

Preference was given to this area largely due to variations in landscape features. The north-western part of the tract is occupied by the extensions of the undulating Malwa Plateau, Manpur being the southernmost site. The landscape forms the southernmost curvature of the Vindhyan range, with its convex side facing the Narmada valley and almost following the 300 m contour line.

This landscape expresses itself in different forms, including the conical peak Singarchori, the flat-topped higher summits of Janpao, Shejgarh etc., plateaux in the north-west, depressions below hills traversed by the headwaters of rivers, spurs extending in all directions, sharp divides, river gorges, and falls to the scarps highly dissected and diversified by streams showing a ''dendritic and radial pattern'' (Zernitz, 1932: 499, 506). Subaerial weathering has played a significant role, and imprints of a few cycles have been obliterated by the cruel hand of time. The climate in general is of the tropical monsoon type and can be placed in the tropical thermal belt according to Thornthwaite's CA¥w classification (where C = subhumid, A¥ = tropical, and w = winter dry). There are typical forests of the Central Indian Highland class, including *Tectona grandis* (teak, known locally as *sagwan*).

The ''present is the key to the past'' preached by Hutton in 1788 served as a base for various geomorphological studies, as it does to the present analysis. It is true that ''The patterns which streams form are determined by inequalities of surface slope and inequalities of rock resistance. This being true it is evident that drainage patterns may reflect original slope and original structure or the successive episodes'' (Zernitz, 1932: 498). Doornkamp and King (1971: 3) also emphasize that the analysis of drainage basins, either as single units or as a group of basins which taken together comprise a distinct morphological region, has particular relevance to geomorphology. Drainage analysis belonging to ''surficial geodynamics'' (Glock, 1931: 475) which, *inter alia*, reveals the work of geomorphic process including ''mass, energy, time, distance, velocity and movement'' (Dikshit, 1987: 11). The drainage area of a basin is the area of its horizontal projection, as determined by planimetry, less the areas occupied by parts not contributing to stream flow, i.e. areas in which stagnant runoff collects (Roger, 1965: 18). Dury (1963: 39) rightly states that ''subjective assessments, however, can be of very little use in comparing one drainage system with another, unless they are made by a single observer who maintains a constant standard of judgement. It is now possible to supersede subjective assessment and qualitative descriptions by quantitative measurement.'' The latter in terms of morphometric evaluation may serve the present purpose well. Morphometry significantly evaluates hydrologic parameters of drainage basins. A few main contributors to the method of morphometric analysis of basin characteristics are Zernitz (1932), Horton (1932, 1945), Miller (1953), Smith (1950, 1958), Strahler (1952, 1953, 1957), Schumm (1956, 1963), Chorley (1958), Woodruff (1964), Mueller (1968), Singh (1967), Singh (1980), Doornkamp and King (1971), Gardiner (1982), and Singh and Singh (1990).

This study is primarily based on published topographical sheets (1:63360) of the Survey of India and data derived by computation and also by observation in the field. All areas were measured by planimeter and lengths of segments by rotameter. The tract was divided into 1 km^2 grids for measurement of these parameters. Thus a drainage network of eight main streams and eight sample tributaries was analysed in terms of drainage density/texture, stream frequency, stream numbers/orders, valley thalwegs (meaning "valley way"), bifurcation ratio, and ratios of elongation, circulation, and length as devised by Horton (1945: 275–370) and applied by others. Maps prepared for relief gradient, profiles, and field survey supplemented the study to make it complete qualitatively as well as quantitatively.

Drainage texture

The texture of erosional topography is determined by natural as well as map factors. Strahler (1953: 1479) suggested two general classes of descriptive numbers: linear scale measurements and dimensionless numbers as a means of measuring size and form properties of drainage basins. Drainage density as a linear scale measurement deserves treatment for a fluvial eroded terrain of the study area (Strahler, 1957: 911). The scale of fineness or coarseness of the pattern is described by measures termed as drainage density and stream frequency (Smith, 1950: 655). Drainage density is defined as the length of stream per unit area in a given drainage basin, and may be expressed by the equation $Dd = \sum L/A$ in which $\sum L$ represents the total length of streams and A represents the area, both in units of the same system. The term "texture" has been used in much the same sense as both "drainage density" and "stream frequency".

The whole range of the drainage texture has been classified into five groups and qualitative nomenclature has been used for quantitative limits, as suggested by Singh (1967: 3).

Less than 2 km/km^2 = Tvc (very coarse texture)
2–3 km/km^2 = Tc (coarse texture)
3–4 km/km^2 = Tm (medium texture)
4–5 km/km^2 = Tf (fine texture)
5 and above km/km^2 = Tvf (very fine texture).

These texture categories show an uneven distributional pattern (Table 4.1). Maximum occurrences fall in the medium and coarse categories. Tvc and Tc combined constitute about 44 per cent of the total, which is almost equal to the occurrences of the Tm category. The last group of fine categories, Tf and Tvf, share only 12 per cent. Lack of fine texture in most of the area indicates the "late maturity" stage of landform development.

An appraisal of Table 4.2 reveals that maximum occurrences lie in the Tm group within an altitudinal limit of 550–775 m. The second maximum

Table 4.1 Drainage density categories

Drainage density range (km/km^2)	No. of grids of 1 km^2	Cumulative area in total	%	Categories
0–2	74	–	20.40	Very coarse (Tvc)
2–3	84	158	23.20	Coarse (Tc)
3–4	161	319	44.50	Medium (Tm)
4–5	26	345	7.20	Fine (Tf)
5 and above	16	361	4.40	Very fine (Tvf)
Total	361		100	

falls in the Tc category in the same altitudinal limit. Hence, coarse to medium texture is associated with the intermediate height group. Very fine texture is absent at heights above 775 m and below 400 m, the areas of ridge summits and low plains. When computed statistically the mean of absolute relief is 2,050′ (625 m) and that of texture 3.52. The standard deviations are 375′ (115 m) and 1.11 respectively. The coefficients of variations are 18.2 per cent and 31.5 per cent, and two variables are negatively correlated, the (r) correlation coefficient being −0.05. The reason may be ascribed to the vast extent of medium height groups in the area, which is an almost plain-like plateau.

An appraisal of Table 4.3 reveals that low relative relief is associated with coarse to medium texture only. Fine texture is a characteristic of moderate to high relative relief.

The maximum occurrences lie in the Tvc to Tm groups along with Rm and Rel categories of relative relief. Coarse to medium texture indicates the late maturity stage of landform development in most of the area

Table 4.2 Altitude/drainage categories: A two-way classification

Altitude groups (m)	Drainage categories with number of 1 km^2 grids						
	Tvc	Tc	Tm	Tf	Tvf	Total	%
Less than 400	1	4	9	5	0	19	4.2
400–475	1	1	5	3	4	14	3.7
475–550	5	9	12	4	2	32	8.8
550–625	42	20	44	4	3	113	31.2
625–700	9	20	52	3	1	85	23.5
700–775	11	24	25	2	6	68	18.8
775–850	3	5	13	4	0	25	6.9
850 and above	2	1	1	1	0	5	1.3
Total	74	84	161	26	16	361	
%	20.4	23.2	44.5	7.2	4.4		

Table 4.3 Relative relief and drainage categories

Relative relief groups (m)	Drainage categories with number of 1 km^2 grid squares						
	Tvc	Tc	Tm	Tf	Tvf	Total	%
0–15 (Rel)	39	18	18	0	0	75	20.7
15–30 (Rm1)	8	12	17	0	0	37	10.2
30–60 (R1)	10	10	19	2	1	42	11.6
60–120 (Rm)	8	28	52	13	5	106	29.3
120–240 (Rmh)	8	12	39	8	6	73	20.2
240 and above (Rh)	1	4	16	3	4	28	7.7
Total	74	84	161	26	16	361	
%	20.4	23.2	44.5	7.2	4.4	–	100

under study. Variation in texture distribution is found between and within the physiographic units as well as drainage basins. Association of Tvf with Rmh and Rh reveals the ‘‘youth’’ stage of landform development in some parts.

The very coarse texture (Tvc) is a characteristic of flat, low-lying areas of the Chambal, Karam, and Dagriakhal river basins. A few portions of the Ajnar valley show these same values. Flat-topped summits and low plains, here and there, do mark the region. The flat-topped summits of Janpao, Singarchori, Samne-ki-mal, Shejgarh, and north of Ghoraghat, Dholgunda, Kaniriya, and Chota jam, are examples.

The coarse drainage texture Tc has no uniform pattern. It follows the upper slopes of valleys and the dissected topography on the ridges or on plateaux. Vast areas in the Karam-Ajnar basin, on the Janpao divide, and elsewhere having such terrain are examples of coarse drainage texture Tc. It is only natural in the undulating landscape of trap areas. Even the wider divides of Topaliya, Bauria, Chhapria, and Indhariya and lower slopes along the hills exhibit coarse texture. Some saddle areas have such texture.

The medium drainage texture predominates in areal extension as well as in marked continuation. The flanks of divides of the Janpao-Singarchori-Hiranmal groups, of Shejgarh, and flanks of escarpments are conspicuously characterized by such texture. Spurs of hills, dissected terrain areas of the Ajnar basin, separate hillocks like those of Yeshwantnagar and Barkhya, and upper catchment areas of the Sukar River all represent medium texture.

The fine drainage texture, Tf, is a characteristic feature of the higher slopes of narrow divides and escarpment zones, and also of some river basins. The narrow divides in the east between Janpao and Singarchori, along with semi-circular catchment areas of the Nakheri, Dagriakhal, and Berchha tanks in the east, those of Karam in the west, gorge valleys of the Ajnar, the uppermost catchment zone of the Sukar, and steep slopes of the escarpment zone in the south account for higher values of 4–5 km/km^2. Here the number of small tributaries increases on slopes, hence the increase in density. Moreover, the semi-circular basin areas in between hill spurs share a larger number and length of streams.

The last category of very fine texture, Tvf, is also represented by narrow divides of Janpao in the western offshoot, and in other areas by the upper reaches of the Karam, Nakheri, Junapani, Maheshwari, Sel, Sukar, and Ajnar. The dissected parts of Pirghata and Bhogliya in the west exhibit this type of terrain in the lower Ajnar basin.

Drainage frequency

Stream frequency is defined as the number of streams per unit area in a given drainage basin, and may be expressed by the equation $Fs = N/A$, in which Fs represents stream frequency and N equals the total number of streams in a drainage basin of A areal units.

The frequency of drainage lines measured in grids of 1 km^2 reveals some interesting features of erosional processes as well as the influence of slope and gradient. The poor-frequency areas lie on the flat surfaces of level to gentle slopes, including the plateau in the north-west drained by the Chambal, Choral, and Karam, which has up to four streams per square kilometre. A similar small area also lies around Khurda in the Ajnar basin. The medium-frequency zone lies on the junction of hill slopes and the plateau. It is remarkable that frequency of streams increases where the gradient is less steep. High-frequency lines of 10 are localized in some parts, such as high peaks and divide zones and lower slopes of escarpments. A still higher frequency line of 12 is a distinct feature of narrow divides. The maximum occurrence of higher frequency lies in the escarpment zone on the lower slopes, where foothill torrents emerge in huge numbers. These higher frequencies are measures to show the early stage of the fluvial cycle or rejuvenated erosional activities in the present study area.

Valley thalwegs

The thalweg (valley way) of a river is the curve of the river course from source to mouth. Such curves, drawn along the winding line of the valley floor, present the concave graded curve of maturity, or convexities or breaks of slopes. The latter signify arrested grading by resistant rocks or differences in rate of valley lowering due to change of rock type or reju-

Table 4.4 Thalweg parameters of basins

No. and name/ gradient of basin	Relief range (m)	Total relief (m)	Channel length (km)
1 Chambal River 1/51	747–549	198	10.90
A Kuvali Nadi 1/52	686–564	122	06.30
2 Karam River 1/70	762–503	259	23.37
B Undwa Nadi 1/69	671–533	138	09.50
3 Ajnar River 1/66	762–412	350	23.10
C Manpur Nala 1/27	640–457	183	05.00
D Khurda Nadi 1/44	747–564	183	08.00
4 Sukar River 1/30	762–442	320	09.60
E Ghata Nala 1/07	686–306	380	02.71
5 Dagriakhal Nadi 1/37	762–670	152	05.60
F Magarda Nadi 1/25	732–610	122	03.30
6 Nakheri Nadi 1/40	777–610	167	06.00
7 Choral River 1/33	762–625	137	05.00
8 Maheshwari 1/16	655–306	349	05.00
9 Jamanjhiri 1/21	720–500	220	04.70
10 Dholgunda Nala 1/14	550–305	245	03.50

venation. The thalwegs thus provide us with a better understanding of terrain.

Valley thalwegs of eight rivers (six tributaries) have been drawn. The profiles themselves prove that the attainment of maturity is reached earlier in large valleys than in small ones, and earlier in the main streams than in their tributaries. Some of the rivers show an almost graded course, but breaks of slopes at different elevations in the Ajnar and its tributaries (Table 4.4) indicate possible stages of rejuvenation due to rift valley formation of the Narmada. The Manpur Nala, a tributary to the Ajnar, shows breaks in lower parts. The upper valleys of most of the tributaries seem ungraded. The Chambal, Karam, Dagriakhal, and Nakheri have graded courses, while the Sukar and its tributaries the Ghata Nala and Dholgunda show ungraded profiles. The influence of steep slopes of escarpment (known locally as *ghata*) is obvious in the profiles of the Ajnar and Dholgunda.

The length of the streams along with their gradients and breaks of slope are measured and tabulated in Table 4.4. One can see a contrast in the profiles of rivers flowing on the plateau and those flowing through the escarpment zone. As discussed earlier, these breaks of slopes, in the Ajnar River particularly, indicate rejuvenation due to faulting. The swift-flowing small river channels of the *ghata* area may be compared with the gentler and larger ones on the plateau.

Table 4.5 Drainage network analysis of main and tributary basins

Basin no.	Name of basin	Stream length ratios of basins				Stream length (km)	Drainage density (km/km^2)
		I–II	II–III	III–IV	IV–V		
1	Chambal River	2.16	1.60	5.00	0.56	113.1	2.50
2	Karam River	2.59	1.58	7.70	0.75	116.4	1.25
3	Ajnar River	2.18	2.35	3.90	–	204.9	2.21
4	Sukar Nadi	1.23	1.51	3.21	–	88.3	2.66
5	Sel Nadi	0.95	0.84	–	–	8.2	1.22
6	Maheshwari	0.74	3.60	0.18	–	594.1	3.89
7	Junapani	1.23	1.71	–	–	84.7	3.30
8	Choral	1.58	1.87	1.63	–	146.4	2.99
Total		1.69	1.85	3.47	1.14	918.6	2.54
1	Kuvali	2.71	3.62	–	–	22.6	3.00
2	Undwa	1.39	1.41	6.90	–	54.4	2.33
3	Manpur	1.20	2.21	–	–	15.3	2.28
4	Jamanjhiri	1.84	4.58	–	–	15.7	1.27
5	Khurda Nadi	1.64	4.55	–	–	34.0	3.68
6	Ghata Nala	1.54	1.20	–	–	11.1	3.58
7	Magarda Nadi	1.98	2.00	–	–	15.7	3.03
8	Dholgunda Nala	1.10	2.20	–	–	12.1	3.90

Drainage net analysis

The incision of valleys on the plateau, the predominance of the ephemeral rills, and a number of small streams indicate multicyclic landform development. Table 4.5 presents basin form characteristics for the main rivers as well as eight small streams selected randomly. The Strahler system of ordering (1957: 911–912) has been adopted for the present study.

An appraisal of Table 4.5 reveals that drainage densities of all the streams descending the escarpment are higher. In preparing a drainage net for such measurements it is assumed that if the entire basin forms a definite relationship, these small ones must also have some relationships. The Karam and Ajnar Rivers present the fifth order, but others, being small, extend to the fourth order only. The data were plotted on graph paper where the frequency and length of streams of each order are plotted on the ordinate against order numbers on the abscissa. The graphs show a general adherence to Horton's law (1945: 275–370), which illustrates an increase in stream number as the order value decreases. This makes each curve steep. The relation between drainage length and order shows a tendency towards an exponential curve in some of the streams.

Bifurcation ratio

The ratio between successive orders of streams is defined as the ''bifurcation ratio''. Horton's first law (Horton, 1945: 291) states as follows: ''The numbers of streams of different orders in a given drainage basin tend closely to approximate an inverse geometric series in which the first term is unity and the ratio is the bifurcation ratio.''

If a geometric series exists, ''a straight line series of points results where the numbers of streams of each order are plotted on a logarithmic scale on the ordinate against order numbers on an arithmetic scale on the abscissa'' (Schumm, 1956: 603). Its irregular tendency is discernible from one order to the next order. ''The irregularity of the bifurcation ratio is dependent upon the lithological and geological development of the drainage basins'' (Strahler, 1971: 484). According to Strahler, the ratio of numbers of segments of a given order (Nu) to the number of segments of the higher order $(N+1)$ is termed the bifurcation ratio (Rb). The equation stands as:

$$\mathrm{Rb} = \frac{\mathrm{Nu}}{\mathrm{Nu}+1} \tag{1}$$

where this bifurcation ratio defines the analysis of tributary junction angles. On average there are 3.5 times as many streams of one order as of the next higher order (Strahler, 1957: 914). Table 4.5 shows the Rb between streams of various orders in a few main and tributary basins, e.g. Chambal (7) and, Ajnar (7.5) between n3 and n4 orders, and Jamanjhiri (7) between n1 and n2. Thus the ratio is from 3.3 to 7.0 for the first order, 2.7 to 4.7 for the second order, and 4.5 to 7.5 for the third order in relation to their successive higher orders. Higher bifurcation ratios are the result of a large variation in stream frequency between successive orders. But there are exceptions in the fifth-order streams of the Karam and Ajnar between n4 and n5, showing only 2 Rb. The weighted mean Rb, as suggested by Strahler (1953) and calculated here, is also higher than 3.5 (Schumm, 1956: 603) in most of the streams.

It is concluded that higher values of Rb in main basins indicate a mature topography which is the result of the process of drainage integration. Tributaries mostly show less than 3.5 Rb between n2 and n3 and indicate the effect of rejuvenation as a result of the geologic and tectonic characteristics of the study area.

Mean stream length

The second law of Horton (1945: 275–370) concerns stream lengths: ''The average lengths of streams of each of different orders in a drainage basin tend closely to approximate a direct geometric series in which the first term is the average length of streams of first order'' (Schumm, 1956: 604). Mean stream length (MSL) is a dimensional property revealing the characteristic size of the components of a drainage network and its contributing basin surfaces. It has been measured by rotameter from topographical maps and then calculated with the help of equation 2:

$$\mathrm{Lu} = \frac{\mathrm{L}}{\mathrm{Nu}} \tag{2}$$

where ''Lu'' is the mean stream length, ''L'' is the total stream length, and ''Nu'' is the number of segments (N) of streams of stream order (u). Orderwise plottings of lengths on an arithmetic scale also show the inverse geometric relation. Disturbed relations of the Karam and Ajnar in the fourth and fifth orders and of the Sel and Maheshwari streams in the first and second orders may be attributed to the sinuous courses in their upper reaches.

Stream length ratio

Horton (1945: 291) also suggested length ratio (RL) as the ratio of the mean length (Lu) of the segments of order (u) to the mean length of segments of the next lower order (Lu – 1), which has been calculated on the basis of equation 3:

$$\mathrm{Rl} = \mathrm{Lu}/\mathrm{Lu} - 1 \tag{3}$$

where Rl is the stream length ratio (SLR), ''Lu'' is the mean stream length of order ''u'', and ''Lu – 1'' is the mean length of the segments of the next lower order. The SLR (see Table 4.5) between the first and second orders is less than 1.0 in the Sel and Maheshwari in the Narmada valley and more than 2.0 in the Chambal, Karam, Ajnar, and Kuvali flowing through higher altitudes. The SLR between second- and third-order streams ranges from 0.84 in the Sel to 4.58 in the Jamanjhiri sample basins. Again it is lowest, 0.18, in the Maheshwari (between third and fourth orders), and goes up to 7.70 in the Karam. Only the Chambal and Karam belong to the fifth order, with their SLRs (between fourth and fifth orders) being 0.56 and 0.75 respectively.

Relief ratio

The relief ratio is defined as ''the ratio between the total relief of a basin (elevation difference of lowest and highest points of a basin) and the

Table 4.6 Relief, elongation, and circularity ratios and form factor of selected drainage basins

			Elongation ratio		Circularity ratio		
Basin no.	Basin name	Relief ratio	Basin length (km)	Maximum elongation ratio	Basin form perimeter factor (km)	Circu-larity ratio	I
1	Kuvali Nadi	0.023	5.25	0.59	14.50	0.45	1.43
2	Undwa Nadi	0.015	8.65	0.63	27.40	0.39	2.69
3	Manpur Nala	0.045	4.00	0.73	12.50	0.57	1.67
4	Jamanjhiri	0.049	4.50	0.63	12.70	0.50	1.42
5	Khurda Nala	0.027	6.60	0.61	19.00	0.44	1.92
6	Ghata Nala	0.140	2.70	0.74	8.25	0.54	1.15
7	Magarda Nadi	0.037	3.30	0.78	10.50	0.59	1.57
8	Dholgunda Nala	0.081	3.00	0.66	8.40	0.55	1.03

longest dimension of the basin parallel to the principal drainage line" (Schumm, 1956: 612). Thus it is a dimensionless height-length ratio showing gradient equal to the tangent of the angle formed by two planes intersecting at the mouth of the basin, one representing the horizontal, the other passing through the highest point of the basin. Rh (relief ratio) is calculated by using equation 4:

$$\mathrm{Rh} = \mathrm{H}/\mathrm{Lb} \tag{4}$$

where H is the total relief and Lb is the basin length. Table 4.6 shows that Rh values vary from 0.023 to 0.140, the minimum being for the Kuvali passing through plateau and the maximum for the Ghata Nala descending from hills; the gradient being 1/52 and 1/07 respectively (see Table 4.4). These Rh values are self-explanatory in giving details of the terrain through which streams are flowing.

Elongation ratio

Schumm (1956: 612) defines the elongation ratio as "the ratio between the diameter of circle with the same area, as the basin and the maximum length of the basin". This ratio is obtained by using equation 5:

$$\mathrm{Re} = \frac{\mathrm{D}}{\mathrm{Lb}} \tag{5}$$

where D is the diameter of the circle having the same area as the basin and Lb is the basin length.

Circularity ratio

Like the elongation ratio, Miller (1953: 8) used a similar measure called a circularity ratio, which is the ratio of the circumference of a circle of the same area as the basin to the basin perimeter. It is affected by the lithological character of the basin. The formula stands as equation 6:

$$RC = \frac{\text{Area of basin}}{\text{Area of circle}} = \frac{4pA}{P2} \tag{6}$$

where RC is basin circularity, P is basin perimeter, 4 is a constant value, $p = 3.14286$, and A is the area of the basin. Table 4.6 indicates the stage of dissection in selected basin areas. The value ranges from 39 to 44, a medium ratio representing early maturity, and 45 to 59, representing maturity stage in the upper reaches of the main rivers. Summit areas of the Magarda, Ghata Nala, and Dholgunda in the Narmada valley show higher values. Anomaly amongst the values also indicates variation of slope and relief.

Form factor

The form factor is also a dimensionless index to indicate the form outline of a drainage basin. It is derived based on equation 7:

$$Rf = A/Lb \tag{7}$$

where Rf is the form factor, A is the area of the basin, and Lb is the length of the basin. Table 4.6 shows that all basins have high values, hence elongated shapes.

Sinuosity index

Geomorphologists, hydrologists, and geologists use this index for interpreting the significance of streams in landform development. Sinuosity deals with the pattern of the channel of a drainage basin. Its value varies from 1.0 to 4.0 or more. Streams having sinuosity indices of less than 1.5 are called sinuous, and those having values of 1.5 or above are called meandering. Streams equal to the valleys, streams slightly smaller than the valleys, and streams small compared to valleys indicate youth, maturity, and old stages of topography respectively (Mueller, 1968: 372). Mueller developed methods of computation of sinuosity indices. He also defined two main types, topographic and hydraulic sinuosity indices, concerned with the flow of natural stream courses and with the development of

Table 4.7 Sinuosity indices of selected tributary basins of Manpur and environs

Basin no.	Name of basin	CL (km)	VL (km)	Air (km)	CI	VI	CSI	HSI	TSI	SSI
1	Kuvali Nadi	6.3	5.25	5.0	1.26	1.05	1.20	0.81	0.19	1.20
2	Undwa Nadi	9.5	8.65	8.0	1.19	1.08	1.10	0.58	0.42	1.10
3	Manpur Nala	5.0	4.00	3.6	1.39	1.11	1.25	0.72	0.28	1.25
4	Jamanjhiri	4.9	4.50	4.4	1.11	1.02	1.09	0.82	0.18	1.09
5	Khurda Nala	8.0	6.60	6.0	1.33	1.10	1.21	0.70	0.30	1.21
6	Ghata Nala	2.8	2.70	2.6	1.08	1.04	1.04	0.50	0.50	1.04
7	Magarda Nadi	3.8	3.30	3.2	1.19	1.03	1.15	0.84	0.16	1.16
8	Dholgunda Nala	3.5	3.00	2.7	1.30	1.11	1.17	0.63	0.37	1.17

floodplains respectively (Mueller, 1968: 372–375). For computation of various type of sinuosity indices the following formulae have been used (Mueller, 1968: 375).

- Channel index (CI) = channel length (CL)/air distance of the stream (determines hydraulic and topographic sinuosity).
- Valley index (VI) = valley length/air distance of the stream (determines, along with index CI, other indices).
- Hydraulic sinuosity index (HSI) = percentage equivalent of CI–VI/CI–1.
- Topographic sinuosity index (TSI) = percentage equivalent of VI–1/CI–1.
- Channel sinuosity index (CSI) = CL/VL.
- Standard sinuosity index (SSI) = CI/VI.

According to Mueller (1968: 373), topographic sinuosity is outstanding during youth when hydraulic sinuosity is negligible; conversely, hydraulic sinuosity is outstanding during the old stage after most of the topographic sinuosity has been removed.

Table 4.7 reveals that CSI ranges from 1.04 in the Ghata Nala to 1.17 in the Dholgunda Nala and 1.25 in the Manpur Nala – all showing a comparatively less sinuous nature in their courses. TSI ranges from 16 per cent to 50 per cent, again showing low values. HSI is high in all streams except the Ghata Nala. These values indicate early maturity to maturity stages of landform development. But the lack of meandering course in most of the streams and lower value of SSI indicate departure from the normal. This is due to the presence of spurs and high watersheds running parallel to streams as limiting factors. On the basis of SSI the drainage basins are classified into two stages of geomorphic development: youthful (less than 1.15), and early mature (1.15–1.30). Thus the Undwa Nadi, Jamanjhiri, and Ghata Nala basins fall in the youthful stage and the remaining five basins are in the early mature stage of development.

Conclusion

The two-way classification of relief and drainage texture indicates larger coverage of the area by coarse to medium texture. Their maximum occurrences, lying in Rm and Rel categories of relative relief, also indicate the late maturity stage of landform development in most of the area under study. Thalwegs and drainage network analysis tell the story of multicyclic development of the landscape. It is observed that analysis of parameters of eight selected drainage basins, in particular, confirms the morphometric laws worked out and proven by Horton and Strahler. Values of bifurcation ratio, including weighted mean bifurcation ratio, mostly higher than 3.5 indicate normal drainage development showing the mature stage. Relief ratio and gradient also show medium values. The elongation and circularity ratios show elongated shapes of basins but are indicative of the early maturity stage. Sinuosity indices indicate early maturity to mature stages of landscape development. It is concluded that the study area shows a polycyclic landscape with a few basins in the youthful stage and others in early mature stage of landform development.

Now is the time for geographers to engage further with theory from discourses such as environmental justice, political ecology, environmental politics, and environmental ethics (Oelofse and Scott, 2002: 43).

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Notes

1. "Sustainable utilization" is the official term adopted by the IUCN in 1980 to denote a rate of resource take which equals the rate of renewal, restoration, or replenishment (O'Riordan, 1989).

REFERENCES

Chorley, R. J. 1958. "Aspects of the morphometry of a 'poly-cyclic' drainage basin", *Geographical Journal*, Vol. 124, No. 3, pp. 370–373.

Chorley, R. J. (ed.). 1969. *Water, Earth and Man: A Synthesis of Hydrology, Geomorphology and Socio-economic Geography*. London: Methuen.

Davies, R. J. 2001. ‘‘The stage of geography’’, in J. Fairhurst, R. Davies, P. Goldshagg, M. Ramutsindela, R. U. Fox, and M. Khosa *State of the Discipline Project: What is the Way Ahead?*, paper presented at the Biennial Conference of the Society of South African Geographers, July, Goudini Spa, Western Cape.

Dikshit, K. R. 1987. ‘‘Trends in geomorphology’’, key address to International Symposium on Geomorphology and Environmental Management, Department of Geography, Allahabad University, January.

Doornkamp, J. C. and C. A. M. King. 1971. *Numerical Analysis in Geomorphology: An Introduction*. London: Edward Arnold, p. 3.

Dury, G. H. 1963. *The Face of the Earth*. Harmondsworth: Penguin.

Fuggle, R. F. and M. A. Rabie. 1999. *Environmental Management in South Africa*, 2nd edn. Cape Town: Juta.

Gardiner, V. 1982. ‘‘Drainage basin morphometry: Quantitative analysis of drainage basin form’’, in H. Sharma (ed.) *Perspectives in Geomorphology*, Vol. II. New Delhi: Concept Publishing.

Glock, W. S. 1931. ‘‘The development of drainage system: A synoptic view’’, *Geographical Review*, Vol. 21, pp. 475–482.

Horton, R. E. 1932. ‘‘Drainage basin characteristics’’, *Transactions of the American Geophysical Union*, Vol. 13, pp. 350–361.

Horton, R. E. 1945. ‘‘Erosional development of streams and their drainage basins: Hydrological approach to quantitative morphology’’, *Bulletin of the Geological Society of America*, Vol. 56, No. 3, pp. 270–275.

Hughes, D. 2002. ‘‘Issues of contemporary geographical hydrology’’, *South African Geographical Journal*, Vol. 84, No. 1, pp. 139–144.

King, J. M., R. E. Tharme, and M. S. de Villiers. 2000. *Environmental Flow Assessment for Rivers: Manual for the Building Block Methodology*, Report No. TT 131/00. Pretoria: Water Resource Commission.

Meadows, M. E. and T. R. Hill. 2002. ‘‘Issues of biogeography: Diversity in theory and practice in the south’’, *South African Geographical Journal*, Vol. 84, No. 1, pp. 116–124.

Messerli, B. 2001. ‘‘Global change and mountain regions: The International Year of the Mountains 2002’’, *IGU Newsletter*, Nos. 3/4, p. 3, available at www.igu-net.org.

Miller, V. C. 1953. ‘‘A quantitative geomorphic study of drainage basin characteristics in Clinch Mt area Virginia and Tennessee’’, Technical Report No. 3. New York: Department of Geography, Columbia University.

Mueller, J. E. 1968. ‘‘An introduction to the hydraulic and topographic sinuosity indexes’’, *Annals of the Association of American Geographers*, Vol. 58, No. 2, pp. 371–385.

Oelofse, C. and D. Scott. 2002. ‘‘Geography and environmental management in South Africa’’, *South African Geographical Journal*, Vol. 84, No. 1, p. 43.

O’Riordan, T. 1989. ‘‘The challenges for environmentalism’’, in R. Peet and N. Thrift (eds) *New Models in Geography*, Vol. 1. London: Unwin Hyman, pp. 93–94.

Roger, J. M. D. 1965. *Geohydrology*. New York: John Wiley & Sons.

Schumm, S. A. 1956. ‘‘Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey’’, *Bulletin of the Geological Society of America*, Vol. 67, No. 5, pp. 597–646.

Schumm, S. A. 1963. ‘‘Sinuosity of alluvial rivers of the Great Plains’’, *Bulletin of the Geological Society of America*, Vol. 74, No. 9, pp. 1089–1099.

Singh, K. N. 1980. *Quantitative Analysis of Landform and Settlement Distribution in Southern Upland of Eastern Uttar Pradesh*. Varanasi: Vimal Prakashan, pp. 125–130.

Singh, R. L. 1967. ‘‘Morphometric analysis of terrain’’, presidential address, Indian Science Congress, Geological and Geographical Section, Hyderabad.

Singh, R. Y. 1979. ‘‘Physical landscape around Manpur, Indore, MP, India’’, *Journal of Scientific Research, Banaras Hindu University*, Vol. XXIX, No. 1, pp. 91–112.

Singh, R. Y. and Singh, H. L. 1990. ‘‘Drainage analysis of a few river basins in Bilaspur region, HP’’, *Transactions of the Institute of Indian Geographers*, Vol. 12, No. 2, July, pp. 122–138.

Smith, K. G. 1950. ‘‘Standards for grading texture of erosional topography’’, *American Journal of Science*, Vol. 248, pp. 655–668.

Smith, K. G. 1958. ‘‘Erosional processes and Badlands National Monument, South Dakota’’, *Bulletin of the Geological Society of America*, Vol. 69, No. 8, pp. 975–1008.

Strahler, A. N. 1952. ‘‘Hypsometric area-altitude analysis of erosional topography’’, *Bulletin of the Geological Society of America*, Vol. 63, No. 11, pp. 1117–1142.

Strahler, A. N. 1953. ‘‘Dimensional analysis in geomorphology’’, *Journal of Geology*, Vol. 62, pp. 571–576.

Strahler, A. N. 1957. ‘‘Quantitative analysis of watershed geomorphology’’, *Transactions of the American Geophysical Union*, Vol. 38, No. 6, pp. 911–938.

Strahler, A. N. 1964. ‘‘Quantitative geomorphology of drainage basin and channel networks’’, in V. T. Chow (ed.) *Handbook of Applied Hydrology*. New York: McGraw-Hill, pp. 39–76.

Strahler, A. N. 1971. *Physical Geography*. New Delhi: Wiley Eastern, pp. 484–492.

Woodruff, J. F. 1964. ‘‘A comparative analysis of selected drainage basins’’, *Professional Geographer*, Vol. XVI, No. 4, pp. 15–20.

Zernitz, E. R. 1932. ‘‘Drainage patterns and their significance’’, *Journal of Geology*, Vol. 40, No. 6, pp. 498–521.

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Part II

Environmental impact assessment in the headwater regions of India and Africa

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5

Environmental changes and status of water resources in the Kumaon Himalayas

P. C. Tiwari and Bhagwati Joshi

Introduction

Water is one of the most fundamental and critical natural resources on the earth. We depend on water for a wide range of values and uses. It plays a crucial role in all sectors of activity, such as domestic, agriculture, industry etc. In a large measure, the development and productivity of a wide range of natural resources depend on the availability of surface water and groundwater. Besides, water offers a multitude of recreational opportunities that are enjoyed by humans. Our awareness of the importance of water to the global environment is changing the future of water resource management around the world. Over the past decade water, particularly surface water and groundwater, has emerged as a major consideration in global discussion about sustainable development. Since the UN's Earth Summit held in Rio de Janeiro, Brazil, in 1992, remarkable progress has been made in advancing the worldwide consensus on addressing water management and conservation issues. In the light of increasing industrialization and mounting urbanization across the globe, and the resultant increased demand for water, an increasing number of countries are viewing their water resources as a source of economic wealth and development potential. The management and conservation of water resources are therefore imperative for channelling the process of sustainable development towards desired destinations. The international community recognizes the multiple benefits and roles of water. Given the wide disparities between countries and social and economic priorities, finding a common definition of what constitutes sustainable water management is crucial.

The Himalayas represent one of the geo-dynamically unstable, ecologically fragile, and economically most underdeveloped mountain ecosystems of the planet. Continuous uplift has left these mountain ranges vulnerable to large-scale tectonic movements and landslides, and to the processes of surface removal. Until recently, the Himalayas have been considered merely as an extension of the plains of north India from the point of view of planning and management of natural resources. But our understanding of the problems of hilly and mountainous areas and our approach to their development have undergone a drastic change during the recent years. This change is reflected in the deepening anxiety over the disruption of the ecological balance in the Himalayas and its attendant deleterious effects on the ecology, economy, and community sustainability in the plains of north India (Maithani, 1986).

Over recent years a variety of changes have emerged in the traditional resource use structure in response to increased population pressure and the resultant increased demand for food, fodder, grazing land, water, and other natural resources in the region. This facilitated and also compelled people to utilize the critical natural resources, such as land, water, and forests, beyond their ecological carrying capacity through unscientific and irrational resource development. Large-scale deforestation, mining and quarrying, extension of cultivation, excessive grazing, and of course rapid urban growth and the development of tourism contributed significantly to the depletion of natural resources in the region. Consequent upon this, water resources have been dwindling and diminishing fast throughout the Himalayan ranges, leading to rapid degradation of aquatic ecosystems. The rapid depletion of water resources has not only damaged the fragile ecosystem but also threatened the sustainability of mountain communities directly as well as indirectly.

The Kumaon Himalayas

The Kumaon Himalayas encompass a geographical area of 21,035 km^2 in the eastern part of the newly created Himalayan state of Uttaranchal. They stretch between 28° 44′ N and 38° 49′ N latitudes and 78° 45′ E and 81° 01′ E longitudes. In the north the area is separated from China by the Indo-Tibetan water divide; in the east the River Kali defines its boundary with Nepal; the plains of Ganga make its southern boundary; and in the west the region shares its boundaries with the Chamoli and Pauri districts of the Garhwal Himalayas. Geographically, the region is located between the plateau of Tibet in the north and the Ganga Plains in the south. Kumaon assumes a great strategic significance as its northern and eastern boundaries make international borders with China and Nepal respectively. Physiographically, from south to north the Kumaon Himalayas are constituted by the low-lying foothill belt of Bhaber (the northern extension of the plains of Ganga with coarse deposits), the Siwalik hills, the Lesser Himalayan ranges, the Great Himalayas, and the trans-Himalayas. These physiographic zones are separated by tectonic boundaries – the thrust planes. The absolute relief of the region varies from 204 m to 7,436 m above the mean sea level. Owing to physiographic diversity the region enjoys a variety of climatic regimes, varying from tropical to polar climatic conditions. The physioclimatic complexities obtaining in the region are reflected in a variety of natural vegetation and numerous species of wildlife. Considering its biological prosperity, the region has been identified as one of the biodiversity hotspots of the world (Tiwari and Joshi, 1997). The Corbett National Park, which has the distinction of being the first national park as well as the first tiger reserve in India, and the Nandadivi Biosphere Reserve are situated in the region. Administratively, the region is organized into Kumaon Division, comprising six districts (Udhamsingh Nagar, Naini Tal, Almora, Bageshwer, Champawat, and Pithoragarh), which put together with Garhwal Division lying to its west and comprising seven districts form the newly created Himalayan state of Uttaranchal. The region has a total population of 2,943,199, of whom only 20 per cent are urban dwellers and the remaining 80 per cent live in rural areas.

The water resources of the Kumaon Himalayas

The precipitation which accumulates on the mountain slopes in the form of snow is the principal source of water in the trans-Himalayas and Great Himalayas. In the Lesser Himalayas and Siwalik mountains, rainwater constitutes the surface and subsurface flow systems and also forms the groundwater reserves through percolation and infiltration. The Himalayan watershed can be divided into three categories on the basis of hydrological characteristics.

- Fluvio-glacial watersheds, which are marked by high surface gradient and medium drainage texture, and are confined to the Great Himalayan ranges.
- The Lesser Himalayan region is the domain of fluvio-erosional processes. Watersheds of this region are characterized by comparatively lower surface slopes, high drainage density, and accelerated erosion.
- The watersheds of the fluvio-depositional hydrographic regime are marked with a low geomorphic energy environment, and consequently

the process of deposition is most significant. This regime extends over the areas adjacent to the south of the Himalayan foothills (Rawat, 1988).

Glaciers

The high-altitude areas lying above the snowline, which is about 4,800 m on the external and southern ranges and about 5,600 m on the Indo-Tibetan water divide, are the land of perpetual snow. There are large numbers of glaciers on the slopes of these snow-clad high mountain ranges, which serve as a natural regulator of water and constitute the biggest reservoir of water resources in the region. An area of about 380 km^2 of the Kumaon is under permanent snow cover, accounting for more than 12 per cent of the total geographical area of the region. The Pindari, Milam, Kaphni, Sunderdhunga, Kalaba, Baldhunga, Talkot, and Poting are some of the important glaciers of the Kumaon Himalayas. The Pindari glacier, which extends for about 3 km in length and 300–400 km in width, is situated between the Nandadevi and Nandakot peaks and forms the source of the Pindar River. The Milam glacier, which lies between the Untadhura range to the north-east and the Nandadevi-Nandakot massif to the south-west, has the region's largest catchment area of 211.12 km^2 and a glacier area of 39.50 km^2 (Table 5.1).

The rivers and streams

Kumaon has three river systems – the Alakhnanda, Ramganga, and Kali. Besides the Alakhnanda, the Girthi and Pindar are the principal rivers of the Alakhnanda system. All these rivers are snow-fed and have their source in the glaciers of the trans-Himalayas and Great Himalayas. The principal rivers of the Ramganga system are the Western Ramganga, Gagas, Kosi, and Gaula, which have their origin in the Lesser Himalayan ranges. The Kali system, which consists mainly of the snow-fed rivers of Kuti, Duauli, Gori, Eastern Ramganga, and Saryu, drains the largest part of Kumaon (10,869 km^2) and has the highest average annual water discharge. The average annual discharge of the Kosi and Gaula Rivers, which have their source in the rain-fed slopes of the Lesser Himalayan ranges, is considerably lower (Table 5.2).

Springs and natural lakes

Apart from the glaciers and rivers, springs and natural lakes are important aspects of the geo-hydrology of Kumaon and constitute a significant proportion of the water resources. No detailed geo-hydrological investi-

Table 5.1 Glaciers of Kumaon

Name of catchment	Name of glacier	Catchment area (km^2)	Glacier area (km^2)
Gori	Milam	211.12	39.50
	Kalabaland	60.00	12.00
	Terahar	31.00	4.50
	Shankalpa	19.00	3.20
	Bamlas	46.00	9.00
	Baldhunga	31.00	8.00
	Upper Lawal	40.00	10.00
	Middle Lawal	15.00	2.00
	Lower Lawal	45.00	8.00
	Poting Lawal	30.00	8.00
	Lower Poting Lawal	6.50	2.00
	Talkot	24.00	5.00
	Balati	40.00	10.00
	Upper Ralamgad	26.00	8.50
	Lower Ralamgad	22.00	8.50
Dhauli	Upper Dhauli	12.00	8.20
	Middle Dhauli	19.00	3.10
	Lower Dhauli	130.00	24.50
	Sona	72.00	40.00
	Baling	45.00	3.00
	Sobla Tejanm	22.00	4.00
Lassar	Upper Lassar	131.00	32.10
	Middle Lassar	115.51	26.60
	Lower Lassar	126.60	39.90
Kali	Lower Kali	30.00	5.20
	Upper Kali	10.00	5.00
Kuti	Kuti Yangti	208.00	20.60
Pindar	Pindari	6.40	2.20
	Kaphni	163.00	22.70

Source: Joshi, Joshi, and Dani, 1983

gation of springs has been carried out in the region. But these springs and lakes contribute a major proportion of the flow of the streams, particularly those originating from the Lesser Himalayan and Siwalik ranges. In most parts of the region the springs are recharged by seasonal rainfall. Tectonic activity along the thrust planes and diversified lithology are mainly responsible for the origin of several lake basins in the region; these are scenically beautiful and geologically very interesting. Bhim Tal, with a total area of 11.20 km^2, is the largest lake and Naukuchia Tal, with a maximum depth of 21.90 m, is the deepest lake in Kumaon (Table 5.3). Beyond these, numerous lakes in the Himalayan region

Table 5.2 Main rivers of Kumaon Himalayas and their average monthly discharge

Month	Average monthly discharge in m^3/sec				
	Saryu	Kali	Western Ramganga	Kosi	Gaula
January	5.54	8.41	7.29	2.24	0.98
February	7.84	6.82	9.01	2.14	1.13
March	6.78	7.37	8.04	2.63	0.90
April	4.96	9.63	6.92	2.40	1.08
May	3.73	10.19	6.45	1.77	0.92
June	3.79	12.27	5.36	1.45	1.25
July	5.40	22.79	8.15	4.92	2.75
August	9.38	29.30	16.16	9.26	6.68
September	35.73	30.41	15.71	6.65	3.09
October	12.24	18.43	13.96	4.21	2.12
November	10.59	3.56	11.53	2.38	2.08
December	9.21	11.40	10.52	2.16	1.74
	2.49	4.76	2.96	1.10	0.57

Source: H. Pathak, 1983

have originated by the damming of rivers by landslide debris, fluvio-glacial processes, and contemporaneous folding of the land during the period of lake formation (Mathur, 1955; Ball, 1878).

Water resource potential

A watershed having independent hydrological boundaries is an ideal geo-hydrological unit for the analysis, monitoring, management, and conser-

Table 5.3 Important morphometric attributes of principal lakes of Kumaon Himalayas

Morphometric attributes	Lake				
	Naini Tal	Bhim Tal	Sat Tal	Naukuchia Tal	Khurpa Tal
Altitude (m)	1,938.00	1,345.00	1,320.00	1,320.00	1,610.00
Maximum depth (m)	25.70	24.75	18.00	41.25	38.00
Mean depth (m)	18.55	12.13	NA	21.90	NA
Maximum length (km)	1.46	1.75	0.87	1.05	0.35
Maximum width (km)	0.47	0.53	NA	0.88	NA
Catchment area (km^2)	5.50	11.20	5.00	2.60	0.59

Source: Rawat, 1987

vation of water resources. The geo-hydrological processes of a watershed are controlled and regulated by a set of geographical factors that include precipitation, transpiration, overland flow, infiltration, deep transfer, subsurface flow, etc. The amount of runoff and infiltration, which play a significant role in maintaining the geo-hydrological balance of a watershed, is to a large extent regulated by the complexities of physio-cultural factors, such as surface configuration, lithology, structure, land utilization pattern, etc. H. Pathak (1983), in his study of utilization and potentials of water resources of the Central Himalayas, assumed that on an average the surface runoff in the region accounts for about 49 per cent of the total rainfall.

A study of vegetation hydrology of the Kumaon Himalayas revealed that the vegetal cover plays a dominant role in increasing the rate of infiltration, as the amount of surface runoff is as low as 0.7 per cent of the total rainfall in densely forested areas (P. C. Pathak, 1983). An experimental study of land use and hydrological parameters revealed that in similar geological, climatic, and geomorphic conditions forested, cultivated, and barren land produce 3.2 per cent, 20 per cent, and 10.38 per cent surface runoff of the total rainfall, respectively (Rawat, 1988). However, an investigation carried out for measuring the water volume of the upper Kosi watershed (480.15 km^2) in Kumaon by the Thiessen polygon method brought out the fact that the entire catchment has a volume of water of 210.77 million m^3 (Tiwari, 1995). Table 5.4 shows that the region has huge water potential. The north Kosi micro-watershed, with a total area of 74.90 km^2, has the largest water volume and accounts for more

Table 5.4 Average annual volume of water in different micro-watersheds of upper Kosi catchment, Kumaon Himalayas

Micro-watersheds	Area (km^2)	% of total area of catchment	Volume of water (million m^3)	% of total water volume of catchment
1. North Kosi	74.90	15.60	32.90	15.61
2. Bhutagaon Gad	34.90	7.27	15.30	7.26
3. Dhoni Gad	40.50	8.43	17.76	8.43
4. Sim Gad	53.90	11.23	23.66	11.22
5. Middle Kosi	68.90	14.33	30.26	14.36
6. Nana Kosi	62.05	12.92	27.24	12.92
7. Patia Ron Gad	44.60	9.29	19.56	9.28
8. Khul Gad	55.90	9.56	20.15	9.56
9. Shail-Jamthara Gad	24.50	5.10	10.74	5.18
10. South Kosi	30.10	6.27	13.20	6.28
Upper Kosi catchment	480.15	100.00	210.77	100.00

Source: Tiwari, 1995

Table 5.5 Spring and stream flow in Shail Gad micro-watershed of upper Kosi catchment, Kumaon Himalayas

Total geographical area (ha)	1,014
Spring density (per km^2)	3.06
Average spring discharge (litre/day)	95,250
Stream density (km/km^2)	3.74
Average stream discharge (litre/day)	118,000
Total water-generating capacity of micro-watershed (litre/ha/day)	210.30

Source: Tiwari, 1995

than 15 per cent of the total water volume of the catchment (Table 5.4). This high water volume in the headwater region is explained by the fact that more than 65 per cent of the micro-watershed has inaccessible terrain and consequently has a very sparse population and dense forest cover.

In order to monitor the water flow in streams and springs, an experimental study was carried out in the Shail micro-watershed (10.14 km^2) in the upper Kosi catchment. The density of springs is 3.06 springs per square kilometre, whereas the density of perennial streams was computed to be 3.74 km of stream length per square kilometre (Table 5.5). The total flow of water in the streams of the region was measured as 125,000 litres/day during dry months. At present there are 31 perennial springs in the region, which together discharge more than 95,000 litres of water per day. Considering the geographical area (10.14 km^2) of the micro-watershed, the flow of water in streams and springs is very high. On average the region has a total water-generating capacity of more than 210 litres/ha/day (Tiwari, 1995).

Status of water resource utilization

Despite its huge water potential, the entire region is facing a great scarcity of water for both domestic and agricultural purposes. So far only 7 per cent of the available water resources have been utilized, mainly for household requirements and minor irrigation. Studies conducted in the upper Kosi catchment in the region revealed that out of the 322 villages as many as 210 have been provided with a piped water supply (Tiwari, 1995). But it was observed during field surveys that in most such villages the water supply is irregular and partial. In 63 villages of the region the piped water supply schemes have become blocked or inoperative, mainly owing to low discharge of springs or streams where the water flows into the distribution system or lack of active community involvement and participation. As many as 197 villages in the catchment are facing acute scarcity of drinking water due to underutilization and improper management of water resources. Generally, as one moves up from the valley floors to the mid- and upslope areas and ridges, the availability of surface water and groundwater decreases owing to increased surface gradient and the low water-generating capacity of the land. It has been largely impossible, mainly for economic reasons, to lift water from the rivers flowing down in the valleys to supply the large number of settlements situated on the higher slopes and ridges. This is one of the important reasons for the non-availability of sufficient water for the rural population in Kumaon. This is substantiated by the fact that Almora town, situated along a ridge about 1,500 m above mean sea level, receives only a third of the water fixed as the minimum water requirement for urban centres by the government. The rural population of the Shail micro-watershed, which has a geographical area of 1,014 ha and a water-generating capacity more than 210 litres/ha/day, are not able to get more than 5 litres/person/day of water for all purposes. This state of affairs brings out the fact that in many areas of Kumaon the high water potential is clearly being managed and utilized very poorly and inefficiently, causing great hardship to local people and resulting in the underdevelopment of the entire region.

Out of the total cultivated land (22 per cent of the total area) in Kumaon, only 11 per cent is irrigated. Water resources for irrigation are managed in the Kumaon mainly through the construction of small canals, tanks, lifts (fuel/electric-powered devices raising water from lower elevations to irrigate higher slopes), hydrams (hydraulic lifting/irrigation devices) etc. Canals and tanks are the main source of irrigation, supplying 38 per cent and 37 per cent of the total irrigated area respectively. The irrigated cultivation is mainly confined to valley floors and other low-lying areas where a regular supply of water for irrigation is available round the year. The cultivated land lying on upslope areas and ridges, accounting for about 84 per cent of the total agricultural land in Kumaon, is never irrigated due to non-availability of water.

Environmental changes and their impact on the geo-hydrology

As in other parts of the Himalayas, the traditional resource development process in Kumaon is interlinked with forests, farmland, and livestock (Palni, Maikhuri, and Rao, 1998). More than 75 per cent of the population of the region are dependent on traditional biomass-based cultivation. In order to preserve soil fertility levels and the productivity of land under sustained cropping in such a biomass-based agro-ecosystem, there must be a net transfer of energy from the support area (forests) to arable land. This flow of energy from forest to cultivated land in the Himalayan agro-ecosystem is mediated through livestock, usually in the form of fodder for stall-fed cattle whose manure and labour are later applied to the cultivated land. On average, one unit of agronomic production in the region involves nine units of energy from the surrounding forest ecosystem (Singh, Pandey, and Tiwari, 1984). The forests and cultivated land of the Himalayas are linked in a series of dynamic relationships involving the production, transfer, and consumption of energy. The optimum rate in this system at any time, in terms of balance between areas (forest and arable land) and numbers (human population and cattle units), is one which permits the maximum utilization and consumption of energy produced in the system without impairing the regenerative and restorative capacity of those elements responsible for commensurate energy production (Whittaker, 1989).

In the Himalayan agro-ecosystem, 5–10 ha of well-stocked forest area are required to meet the energy requirements of 1 ha of arable land in order to practise agriculture on a sustainable basis (Singh, Pandey, and Tiwari, 1984). In the upper Kosi catchment, the forest land available per hectare of agricultural land is only 2.77 ha, and more than 60 per cent of these forests are highly degraded. This clearly shows that the biotic stress on the forests of the catchment is very acute. The rapid growth of population, and the resultant increased demand for arable land, grazing areas, fodder, and fuelwood, plus inappropriate development strategies have pushed crop farming into forests and marginal and sub-marginal areas. Expansion of cultivation in the region is now taking place at the rate of 0.79 per cent per year (Tiwari, 1995). Consequently, there is a proportional increase in the cattle population. The availability of grazing area in the region is 0.21 ha per head of cattle against the ecologically recommended minimum standard of 3.5 ha per head (Ashish, 1983). The grazing pressure is very acute, and the pastures are coming under increased grazing stress with the massive increase in cattle population. As a result, the forest and rangelands on average up to 7 km distance from the rural settlements in the region are highly degraded and depleted (Tiwari, 2000, 2002).

As described above, the traditional process of natural resource development has been changing fast, mainly in response to high population growth and resultant increased demand for food, fodder, fuelwood, etc. Consequently, the activities of cultivation, grazing, and deforestation are extended over large areas of the region. The natural ecosystem of the region has come under increased resource use pressure, resulting in ecological imbalances and unsustainable resource development (Bisht and Tiwari, 1996). The proportion of degraded and waste lands has been increasing, and they now account for more than 15 per cent of the total geographical area of the Kumaon (Tiwari, 2002). The rapidly changing land-use pattern and the resultant decrease in forest area have contributed significantly to promoting the process of soil erosion in the region and decreasing the water-generating capacity of the land (Ives, 1989).

Retreat of glaciers

Studies reveal that the glaciers of Kumaon have been receding and becoming smaller in size, and their regulatory effect is diminishing considerably owing to environmental changes. Most of the Himalayan glaciers have had a negative mass balance (i.e. the melting rate is higher than the accumulation rate of snow) during the last 20–25 years (Cotter, 1906; Strachey, 1845; Tiwari, 1972; Rawat, 1988). The receding trend in the Himalayan glaciers is also indicated by several disconnected tributaries in the region which were earlier connected with the main body of the glaciers (Bhandari and Nijampurkar, 1988). The Pindari glacier in the Kumaon Himalayas has retreated by about three kilometres between 1845 and 1966, and its size has diminished by 29 kilometres since the Pleistocene glacial period (Rawat, 1988). The Milam glacier in the region is receding at an average rate of 12.5 m/year (Bhandari and Nijampurkar, 1988). On average, the glaciers of the Kumaon Himalayas are receding at the rate of 23.46 m/year (Rawat, 1988). If this diminishing trend of glaciers continues, the regime of the snow-fed rivers in the region will be adversely affected and the Himalayan rivers will carry far less water as there will be a gradual decrease in the volume of snow-melt water released during the summers (Valdiya, 1985).

Drying of springs

The large-scale depletion of forest resources is causing great damage to underground water resources by reducing the water-generating capacity of the land to supply springs and streams in the region. Since a large proportion of the rainfall is lost through surface runoff without replenishing the groundwater reserves, a large number of springs that support a variety of life-sustaining activities, particularly in rural Kumaon, are drying up fast. A study carried out in the Gaula catchment of Kumaon revealed that about 45–46 per cent of springs have dried up or become seasonal due to reduced groundwater recharge (Valdiya, 1985). In the Shail microwatershed of the upper Kosi catchment, out of 49 natural springs 18 have completely dried up and all the nine flour mills have been abandoned over the last 20–25 years due to low water discharge into streams. The heads of many streams in the region have moved down on average 37 m during the last 25 years. In view of the reduced recharge of groundwater in the watersheds of the region, it is estimated that the Himalayan rivers will carry 20–30 per cent less water in the near future (Valdiya, 1985). These geo-hydrological changes have a large impact not on the geo-ecology but also on the quality of life of rural communities in the region. A study carried out in the upper Kosi catchment revealed that the watershed has lost about 11 per cent of its irrigation potential owing to reduced water flow in steams and springs, and consequently the productivity of the agro-ecosystem has declined by about 9 per cent despite continued extension of cultivation over the last 20–25 years (Tiwari, 1995). Owing to the very low productivity of the traditional agriculture, male youths migrate out of the region in search of better livelihoods, leaving behind large number of females, children, and old people in the region. Consequently, the task of fetching water and collecting fodder and fuelwood from long distances away becomes the sole responsibility of women. A survey carried out in the upper Kosi catchment revealed that the average travelling distance for the collection of potable water has increased from 2 km to 4 km during the last 20–25 years, mainly owing to the drying up of natural springs within and in the surroundings of the rural settlements in the catchment (Tiwari, 1995).

Diminishing lake ecosystems

The lake ecosystems of Kumaon are also under increased biotic stress. Most of the lakes in Kumaon are situated along tectonically active and ecologically fragile but densely populated zones. What is more, all the lakes mentioned in Table 5.3 are situated within or in the surroundings of fast-growing urban areas. More recently, comparatively less accessible areas of the lakes region of Kumaon are also coming under the process of fast urbanization, mainly owing to the extension of road networks, development of horticulture, a gradual shift from primary resource development practices to secondary and tertiary sectors, and the growth of domestic tourism through the publicity and marketing of new tourist sites. The natural risks of this unplanned urban growth are clearly discernible in terms of increased numbers of landslides, accelerated soil erosion, disruption of natural drainage, and silting and pollution of lakes. This is resulting in the depletion and destruction of nature as well as increased incidence and severity of urban environmental hazards in many of the urban centres, such as the lake town of Naini Tal. Bathymetric investigations of Bhimtal and Naini Tal lakes revealed that the capacity of these important lakes has respectively decreased by 5,494 m^3 and 14,150 m^3 over the last 100–110 years due to rapid siltation of the lakebeds. The annual average rate of siltation in Naini Tal lake was 65.32 m^3 (Khanka and Jalal, 1984; Rawat, 1987). Most of the lakes of the region are heavily infested by weeds and invasive marshy conditions (Rawat, 1988).

Conclusions

It is clear from the above discussion that the water resources of Kumaon are diminishing fast owing to the rapid transformation of the natural environment and resultant geo-hydrological disturbances. The huge glaciers of the Great Himalayas and trans-Himalayas are receding fast, and their regulatory mechanism is diminishing. The water-generating capacity of the land is decreasing due to reduced recharge of groundwater in the region. As a result the springs are drying and the water discharge of streams is decreasing. The beautiful lakes of Kumaon are becoming smaller in size and their capacity is dwindling due to anthropogenic impacts in the catchment areas. These geo-hydrological imbalances have a large impact on the fragile ecosystem of the Himalayas as well as on the sustainability of mountain communities.

Forests and farmland are the most crucial components of the traditional resource utilization structure in the Kumaon Himalayas. The natural forests in the region carry a large human population, including forest-dependent tribal groups living interspersed among them. These rural communities are completely dependent on forests not only for the fulfilment of their basic resource needs, such as fuelwood, fodder, timber, grazing etc., but also for their livelihoods. It is therefore not practically possible to conserve natural resources without considering the needs and problems of rural communities living in the area, particularly when their traditional activities are limited or prohibited in many parts of the region following the creation of national parks, sanctuaries, and biosphere reserves. Hence, the environmental conservation and resource development programmes in the region have to be people- and development-oriented. In view of this, the conservation of dwindling water resources in the region is very complex in nature as it is essentially associated with the management of other critical resources, particularly the land and forests. This brings out the fact clearly that the goal of sustainable development of water resources cannot be attained through a sectoral approach. It is therefore imperative to analyse all crucial issues related to conservation and protection of water resources in a holistic manner by considering water conservation and management as one of the essential components of overall land-use and resource development policies. This clearly under-lines the need to develop a natural resources information system (NRIS) at micro-watershed level through comprehensive and detailed analysis, appraisal, and mapping of land, water, and forest resources against the socio-economic backdrops of the region. Remote sensing and geographic information system (GIS) techniques will be highly useful in the analysis and management of natural resources in terms of both time and cost-effectiveness.

REFERENCES

Ashish, M. 1983. ''Agricultural economy of Kumaon hills: A threat to ecological disaster'', in O. P. Singh (ed.) *The Himalaya: Nature, Man and Culture*. New Delhi: Rajesh Publications, pp. 184–197.

Ball, V. 1878. ''On the origin of Kumaon lakes'', *Records*, Vol. XI, Part II, Geological Survey of India, pp. 174–182.

Bhandari, N. and V. N. Nijampurkar. 1988. ''Himalayan glaciers: Our neglected water banks'', in S. K. Chadha (ed.) *Himalayas: Ecology and Environment*. New Delhi: Mittal Publications, pp. 76–92.

Bisht, B. S. and P. C. Tiwari. 1996. ''Land-use planning for sustainable resource development in Kumaon, Lesser Himalaya – A study of Gomti watershed'', *International Journal of Sustainable Development and World Ecology*, Vol. 3, pp. 23–34.

Cotter, G. P. 1906. ''Notes on certain glaciers in Kumaon'', *Records*, Vol. 35, No. 4, Geological Survey of India, pp. 148–151.

Ives, J. D. 1989. ''Deforestation in the Himalaya: The cause of increased flooding in Bangladesh and northern India'', *Land Use Policy*, Vol. 6, pp. 187–193.

Joshi, S. C., D. R. Joshi, and D. D. Dani. 1983. *Kumaon Himalaya: A Geographical Perspective on Resource Development*. Naini Tal: Gyanodaya Prakashan.

Khanka, L. S. and D. S. Jalal. 1984. ''Morphological analysis of Lake Naini Tal in Kumaon Himalaya'', *Geographical Review of India*, Vol. 46, No. 4, pp. 64–69.

Maithani, B. P. 1986. ''Towards sustainable hill area development'', *Himalaya: Man, Nature and Culture*, Vol. 16, No. 2, pp. 4–7.

Mathur, S. M. 1955. ''On the origin of Bhimtal and neighbouring lakes in the Naini Tal district, UP'', *Quarterly Journal of the Geological Mining and Meteorological Society of India*, Vol. XXVII, No. 4, pp. 125–180.

Palni, L. M. S., R. K. Maikhuri, and K. S. Rao. 1998. ''Conservation of the Himalayan agro-ecosystem: Issues and priorities'', Technical Paper V, in *Ecological Co-operation for Biodiversity Conservation in the Himalaya*. New York: UNDP, pp. 253–290.

Pathak, H. 1983. ''Water resources of UP Himalaya: Their uses and potential'', in O. P. Singh (ed.) *The Himalaya: Nature, Man and Culture*. New Delhi: Rajesh Publications, pp. 161–169.

Pathak, P. C. 1983. ''Vegetation hydrology and its impact on nutrient cycling in selected forest ecosystems of Kumaon Himalaya'', unpublished PhD thesis, Kumaon University, Naini Tal.

Rawat, J. S. 1987. ‘‘Morphometry and morphology of Naini Tal, Kumaon, Lesser Himalaya’’, *Journal of the Geological Society of India*, Vol. 30, No. 6, pp. 493–498.

Rawat, J. S. 1988. ‘‘Water resources and burning hydrological problems of Kumaon’’, in K. S. Valdiya (ed.) *Kumaon Land and People*. Naini Tal: Gyanodaya Prakasnan, pp. 201–212.

Singh, J. S., U. Pandey, and A. K. Tiwari. 1984. ‘‘Man and forests: A central Himalayan case study’’, *Ambio*, Vol. 13, No. 2, pp. 80–87.

Strachey, R. 1845. ‘‘A description of the glaciers of Pindari Kaphinee Rivers in Kumaon Himalaya’’, *Journal of the Asiatic Society of Bengal*, Vol. 16, No. 2, p. 203.

Tiwari, A. P. 1972. ‘‘Recent changes in the position of the snout of the Pindari glacier, Kumaon Himalaya, Almora district, UP, India’’, in *Proceedings of the Symposium on Role of Snow and Ice in Hydrology*, Vol. 2. Canada: UNESCO-WHO-IAHS, pp. 1144–1149.

Tiwari, P. C. 1995. *Natural Resources and Sustainable Development in Himalaya*. Almora: Shree Almora Book Depot.

Tiwari, P. C. 2000. ‘‘Land use changes in Himalaya and their impact on the plains ecosystem: Need for sustainable land use’’, *Land Use Policy*, Vol. 17, pp. 101–111.

Tiwari, P. C. 2002. *Second Annual Progress Report of the Research Project on Natural Resources Information System for Wasteland Development in Kosi Headwater*. New Delhi: Department of Science and Technology, Government of India.

Tiwari, P. C. and B. Joshi. 1997. *Wildlife in the Himalayan Foothills: Conservation and Management*. New Delhi: Indus Publishing.

Valdiya, K. S. 1985. ‘‘Accelerated erosion and landslide-prone areas in the central Himalayan region’’, in J. S. Singh (ed.) *Environmental Regeneration in Himalaya*. Naini Tal: Central Himalayan Environment Association, pp. 12–38.

Whittaker, W. 1989. ‘‘The ecology and economy of Himalayan agriculture and labour migration: A case study of Garhwal district’’, in D. C. Pandey and P. C. Tiwari (eds) *Dimensions of Development Planning*, Vol. 2. New Delhi: Criterion Publications, pp. 509–550.

6

Factors regulating fresh water quality in the Himalayan river system

Vaidyanatha Subramanian

Introduction

The mighty rivers draining the Himalayan range show several features that are unique to large rivers of the world. Similar to any other rivers, there are pronounced spatial and temporal variations with respect to both water chemistry and sediment properties. The Ganges shows certain aspects of sediment load and mineralogical and chemical variations that differ considerably from the Brahmaputra. While the Ganges shows the impact of large urban and other land-use components in its properties, the less densely populated Brahmaputra is relatively uncontaminated. Major water quality parameters such as HCO^{3-}, $(SO_4)^{2-}$, $(PO_3)^{3-}$, and SiO_2 are higher in the Ganges compared to the Brahmaputra. Also, larger basin variations are common for the Ganges compared to the Brahmaputra, and the larger variations are attributed to several large tributaries in the Ganges. Both rivers carry a predominant coarse sediment load (with a mean size of about 60 μm) with a similar clay mineral composition, including illite, kaolinite, and chlorite. The Ganges in India is polluted with respect to heavy metals, but the headwaters of the Brahmaputra in India and the combined system in Bangladesh are relatively clean.

The River Ganges originates in the Gangotri glaciers at an altitude of over 7,000 m above sea level and traverses mountains for about 250 km before reaching the plains at Haridwar; thereafter it traverses flat terrain for about 2,500 km before joining the other great river, the Brahmaputra, in the lower regions in Bangladesh. Likewise, the River Brahmaputra originates near Lake Mansarovar and travels for about 1,000 km on the

Tibetian plateau; it then drops in elevation in a short distance from over 3,500 m to about 250 m where it enters India. From here it flows over relatively flat terrain, joins with the Ganges, and flows into Bangladesh. The basin area of the Brahmaputra in Tibet, India, and Bangladesh is 924,000 km^2, of which only 30 per cent is in India. In contrast the basin area of the Ganges is 861,000 km^2. A major tributary, the Megna, joins the combined river system in the lower reaches and has a basin area of about 80,000 km^2. Of the total drainage area of all major rivers in the Indian subcontinent (about 4 million square kilometres), a third is contributed by the Ganges-Brahmaputra-Megna river system as a single combined input to the Bay of Bengal through the Sundarban mangrove swamp which stretches into India as well as Bangladesh. While the Ganges has a large number of major tributaries (Figure 6.1), the Brahmaputra is essentially a single-river system with the world's largest river island, Majouli in Assam, in the middle of the river valley. Figure 6.1 also shows the annual runoff of the various river systems in the Himalayan drainage basin. The estimated annual water discharge to the ocean is around 1,330 km^3 at the river mouth, making it the second largest modern delta in the world. In

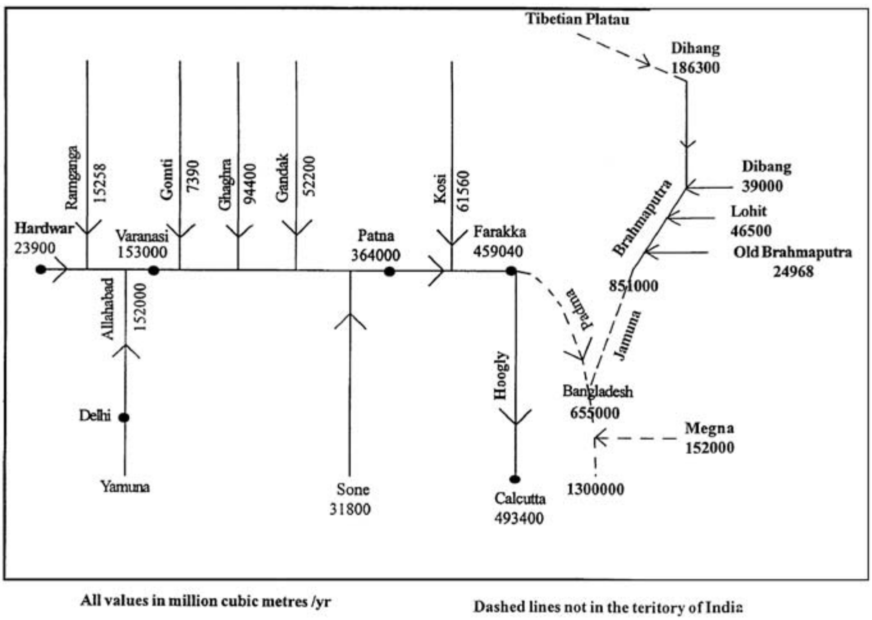

Figure 6.1 Flow diagram for the Ganges-Brahmaputra river system
Notes
Some important locations are also shown. Only some of the important tributaries are shown. Annual runoff in million m^3 is indicated. Bangladeshi and Tibetan parts of the basin are in areas marked by dashed lines. Figure not to scale. Approximate distance from Hardwar to Calcutta 2,300 km.

addition to large alluvial plains, both the river systems together annually deliver about a billion tonnes of sediments to the coastal region, although the actual mass of sediments reaching the open ocean is still a matter of debate. The catchment area geology is primarily the tertiary Himalayan mountain system, with large exposures of sedimentary rocks all along the mountain chain and a scattering of hard rocks at various places and elevations. The Megna is primarily a hard rock terrain with its catchment in the Shillong plateau region in the north-eastern part of the mountain system. Even in the alluvial plains of the Ganges, there are intermittent exposures of gneisses and other hard rocks. The Ganges basin, unlike the Brahmaputra, has diverse geology with tertiary Deccan traps (tertiary basaltic) covering some of the tributary regions. Such a complex river system geology has a bearing on the water chemistry and quality and quantity of sediment load of the rivers at various locations in the vast drainage basin area.

The objective of the present work is to understand various geochemical processes that operate in the large drainage system and how they influence the water chemistry, sediment load and erosion rates, overall weathering as indicated by CIA (chemical index of alteration), and controlling hydrological factors. Attempts have also been made to compare the present observations with those reported for other large river systems in the world.

Materials and methods

Data generation on the river system is a continuous programme and sampling location and frequency follow well-accepted norms, namely tributary junctions, major litho units, urban areas, across river channels wherever possible, and seasonal samples. Types of samples include water, suspended sediments, surface sediments, and short (generally less than a metre in depth) sediment cores at a few locations. Standard APHA (APHA, 1995) analytical procedures have been followed for various parameters, with either chemical standards for water analysis or sediment standards (USGS, IAEA, and others) for sediment chemical analysis.

Results and discussion

In the last monsoon of the last century (the monsoon of 1999), water samples collected from a few locations in the upper reaches of the Ganges and at various locations downstream were analysed along with those of the Brahmaputra in the Bangladesh region. Table 6.1 shows the data for most of the parameters. Li, Sr and NH_4^+ are also reported

Table 6.1 The Ganges in India and Bangladesh, August–September 1999: Chemical analysis of water sample

Concentration in µmol/l											
HCO_3	Cl	PO_4	NO_3	SO_4	Na	K	Ca	Mg	F	Sr	Li
1,100	18	0.10	25	217	56	5	456	123	15	tr	0.14
980	23	0.01	18	167	43	6	778	246	7	tr	0.21
1,000	28	0.01	30	198	57	5	700	205	12	tr	tr
850	93	0.50	132	282	183	10	966	329	10	tr	0.14
1,590	91	0.01	42	243	241	10	1,025	411	12	tr	tr
1,780	1,199	0.10	24	421	2,001	14	1,347	905	21	2.750	tr
1,810	48	0.01	0	209	93	8	1,092	411	5	tr	tr
1,900	45	0.01	3.5	167	139	7	1,144	411	10	0.502	0.21
1,590	117	1.10	6	52	338	5	643	269	15	tr	tr
1,680	237	0.20	138	159	565	6	365	164	10	tr	tr
1,630	197	0.20	157	186	478	7	940	374	13	tr	tr
1,350	113	0.10	0	156	300	8	1,083	385	5	tr	tr
2,227	168	0.10	35	177	368	8	1,477	412	11	0.547	tr
504	60	0.20	0	166	137	6	1,049	261	6	0.376	tr
1,031	26	0.10	0	135	70	4	659	166	4	tr	tr

for the first time at a few locations only, but they are within the normal range reported for many other world rivers. Table 6.2 shows the monsoon chemistry of the Brahmaputra water in India from the Tibetan border to the Bangladesh border over a distance of 1,000 km. Essentially both the river systems have similar water chemistry with respect to

Table 6.2 The Brahmaputra in India, August–September 1999: Chemical analysis of water sample

Concentration in µmol/l								
HCO_3	Cl	PO_4	SO_4	Na	K	Ca	Mg	F
885	114	0.90	23	86	25	300	208	10
934	114	0.50	15	86	51	350	166	5
868	171	0.50	17	86	51	300	208	5
1,000	142	0.60	20	130	51	400	208	5
1,000	114	0.40	18	88	25	425	166	5
967	142	0.70	24	173	76	325	210	5
918	142	0.70	18	86	50	300	166	5
1,000	114	0.70	26	88	51	375	165	5
885	142	0.12	16	86	50	300	166	10
950	142	0.10	20	86	75	350	165	10
1,000	142	0.14	21	88	76	425	125	10
868	145	0.16	19	86	76	300	166	10
1,016	142	0.18	20	86	76	350	125	11

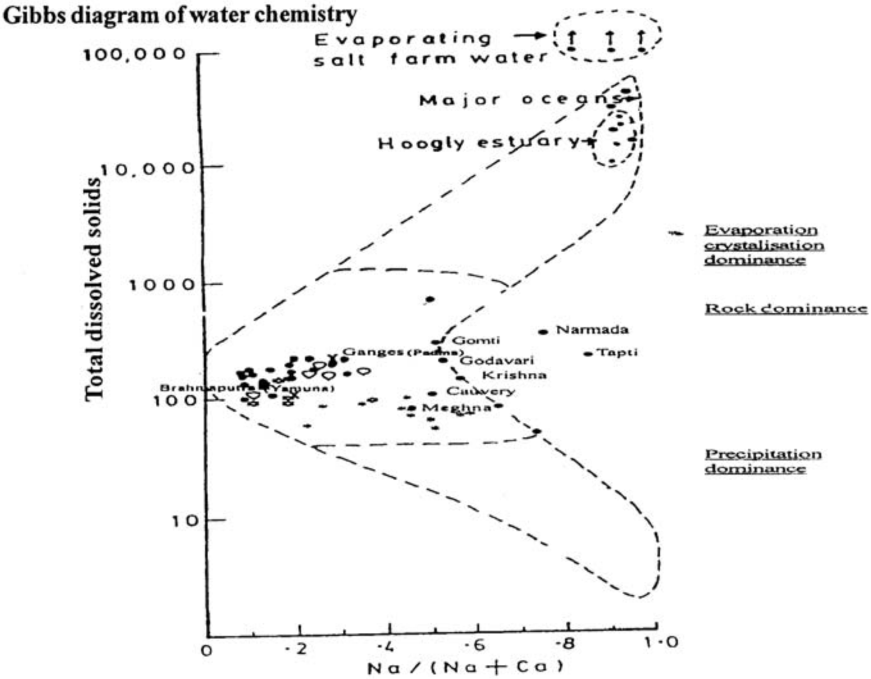

Figure 6.2 Gibbs's diagram for water chemistry for the Himalayan river system
Source: Gibbs, 1970
Notes
Hoogly estuary is the Indian part of the Ganges estuarine region. Some other major rivers in India such as the Godavari, Krishna, and Cauvery are also shown.

the major constituents, though there are small differences in individual parameters at different locations. Due to the low level of population density, the Indian stretch of the Brahmaputra River has lower levels of most of the ions in comparison to the Ganges in both countries and the lower reaches of Brahmaputra in Bangladesh. The water bodies in Bangladesh – both the Brahmaputra (called the Jamuna in that country) part and the combined Ganges (known as the Padma in that country) and Brahmaputra – generally show low levels of HCO_3^- and Cl^-, though the other constituents remain comparable to the upper reaches of both these rivers in India. Because of the turbulent effects of the monsoon rain, there are no distinctions between the monsoon river channels of the Ganges and its numerous tributaries such as the Gandak, Yamuna, and Sone, though geologically each of the tributaries has a separate lithology.

A plot of long-term water quality for these rivers using Gibbs's diagram (Gibbs, 1970), shown in Figure 6.2, suggests the effect of rock weathering on river water chemistry. The estuarine waters in the lowland region, as would be expected, fall in the top portion of the figure due to salt water mixing. Abbas and Subramanian (1984), Datta and Subramanian (1997), and Sarin *et al.* (1989) likewise have observed the control on rock weathering in these drainage basins, while several other workers observed similar findings for many rivers in the world (see, for example, Stallard and Edmond, 1981). The spread of the data points along the x-axis (Na/Na+Ca), as also on the y-axis, indicates wide variation in the contribution of Na, Ca, and total dissolved solids (TDS) to the river water due to diverse geology and soil types in the vast basin area. Overall, the discharge weighted average chemical composition of the water in the entire Himalayan drainage system can be viewed as having a HCO_3^- of 105 mg/l, $Cl^- = 7$ mg/l, $F^- = 0.2$ mg/l, $SO_4^{-2} = 15$ mg/l, $PO_4^{-3} = 0.09$ mg/l, $Na^+ = 7$ mg/l, $K^+ = 2$ mg/l, $Mg^{+2} = 5$ mg/l, $Ca^{+2} =$ 24 mg/l, $SiO_2 = 15$ mg/l, and TDS of about 174 mg/l. Thus the river water has higher levels of solute in comparison to the world average values of Meybeck (1983), as well as most major rivers such as the Amazon and Mekong.

Table 6.3 shows the rainwater composition in the river basins along with the estimated atmospheric contribution to the observed river water chemistry. Analyses of rain and snow in the Himalayan high-altitude regions are also shown. Being a group of islands in the middle of the Bay of Bengal, the rainwater over the Andamans shows clearly their marine origin with dominant Na^+ and Cl^-; surprisingly, the glacier meltwater and snow more than 25,000 km inland also show similar trends. But the rainwater over the Ganges and Brahmaputra basin at various locations in India as well as in Bangladesh shows the continental signature in the form of dominant Ca^{+2} ions. Except for Cl^- and to some extent K^+, the atmospheric contribution is not significant to the river water chemistry.

Following the method of Nesbitt and Young (1982), the chemical index of alteration (CIA) was calculated for the rivers at various locations and also for the suspended and bed sediments separately based on previously published chemical data for sediments (see for example Subramanian, Van t'Dack, and Van Grieken, 1985). Even though the concept of using CIA as suggested by them was to highlight the nature of alteration as reflected in the composition of surface sediments only, in the present case it has also been extended to the suspended sediments since they reflect enrichment or depletion of mobile components due to leaching or removal processes that operate in the water column. The upper reaches of the Brahmaputra in India and a tributary of the Ganges – the Kosi near Patna – show CIA values in excess of 85 for the surface sediments, whereas for all other locations in both rivers and for different seasons

Table 6.3 Major ion chemistry of rainwater in and around Bengal basin

Stations	Concentration in μmol/l						Remarks
	Ca^{2+}	Mg^{2+}	Na^{-1}	K^{-1}	Cl^{-1}	$SO_4{}^{2-}$	
Chapainwabganj, Rajshahi, Bangladesh	11.0	7.0	17.0	21.0	8	5.0	Late monsoon 1991 Ahmed, 1994
Calcutta	99.0	36.0	68.0	9.5	113	36.0	Monsoon 1994 Das, 1988
Calcutta	16.0	5.0	37.0	4.0	28	8.0	Monsoon 1975 Sequeira and Kelkar, 1978
Calcutta	31.0	4.0	36.0	12.0	28	25.0	Monsoon 1968 Handa, 1968
Mohanbari Brahmaputra valley	4.7	2.5	8.5	6.4	20	6.7	Monsoon 1989–1991 Mukhopadhyay, Datar, and Srivastava, 1992
Port Blair, Andaman	17.0	13.0	132.0	8.0	87	5.0	Monsoon 1979–1982 Mukherjee *et al.*, 1986
Chhoto snow	6.0	4.0	17.0	7.0	21	2.0	Nijanpurkar, Sarin, and Rao, 1993
Glacier ice	2.6	1.4	8.0	3.0	11	1.8	Nijanpurkar, Sarin, and Rao, 1993
Godavari basin	82.0	53.0	32.0	23.0	200	7.0	Biksam and Subramanian, 1988
India average	73.0	35.0	56.0	16.0	17	18.0	Biksam and Subramanian, 1988

and different types of sediments (bed and suspended) the CIA values are generally 50 ± 15, indicating the limited chemical alterations of source rock minerals in the catchment areas. Some of the sediments show values even lower than the crustal average of 47, though the sediment mineralogy in these rivers is primarily illite-chlorite dominant with mean particle size of the suspended sediments in the silt range. There is a variable proportion of kaolinite, although it does not seem to change the CIA values significantly. Figure 6.3 shows the nature of spread of the CIA values in the drainage basin without any clear trends either spatially or seasonally. The low CIA values (not corrected for $CaCO_3$) may simply represent an abundance of non-silicious Ca, since these sediments carry a large proportion of $CaCO_3$ concretions physically eroded from the catchment areas in the upper reaches of the Himalayas. Thus the $CaCO_3$-corrected CIA values are expected to be higher than what is estimated, whereas Depetris and Probst (1998) reported a lower CIA value of 71, based on

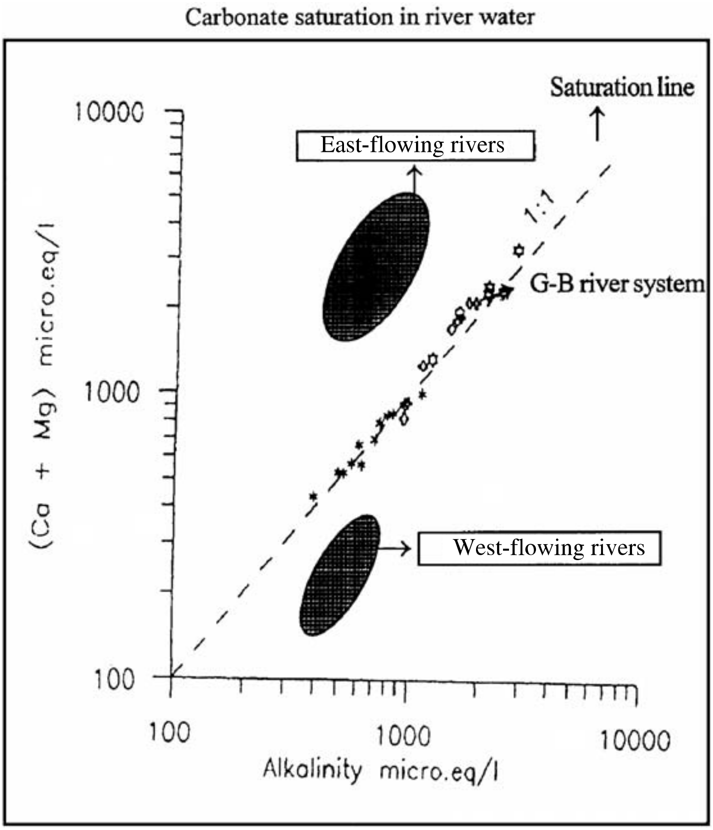

Figure 6.3 Saturation levels of river waters in the carbonate system
Source: Adapted from Staller and Edmond, 1981
Notes
Other large rivers in India as well as smaller west-flowing rivers on the western ghats are also shown. Saturation line for $CaCO_3$ precipitation is also indicated. Data points for the Ganges-Brahmaputra system show only average values.

discharge weighted average composition, in comparison to 81 for the Parana River in South America.

The suspended sediments of the Ganges between Allahabad and Calcutta show CIA values of 60 $\pm$ 10: this is the region of mixing with a large number of major tributaries, such as the Yamuna (draining partly the basaltic terrain), Gandak, Kosi, and Gagra, with high sediment loads. The tributary Kosi has the highest value, at 85, in the entire Ganges river system. The tributary Megna in Bangladesh and the smaller tributaries of the Brahmaputra in Assam show relatively lower values around 60, indicating no significant alteration processes in the river catchment areas. The dominance of illite and chlorite even in the bed sediments of the Brahmaputra in India (Subramanian and Ramanathan, 1996) is perhaps reflected in higher CIA values (generally around 90) in this region. The clay minerals present in the river system here are essentially coarse detrital clays partly degraded from the sedimentary and metamorphic source rock in the catchment. Hence, the CIA values may not truly represent the weathering process in this system. Thus the chemical weathering signature may have been masked by the high sediment load derived by physical weathering, leading generally to lower CIA values.

Figure 6.4 shows the position of the river water composition in the silicate system for the Ganges-Brahmaputra basin. One can see that the data points generally fall in the boundary of plagioclase-illite-smectite conversion, and the river sediments are generally dominated by illite and chlorite with small but variable amounts of kaolinite. Being very

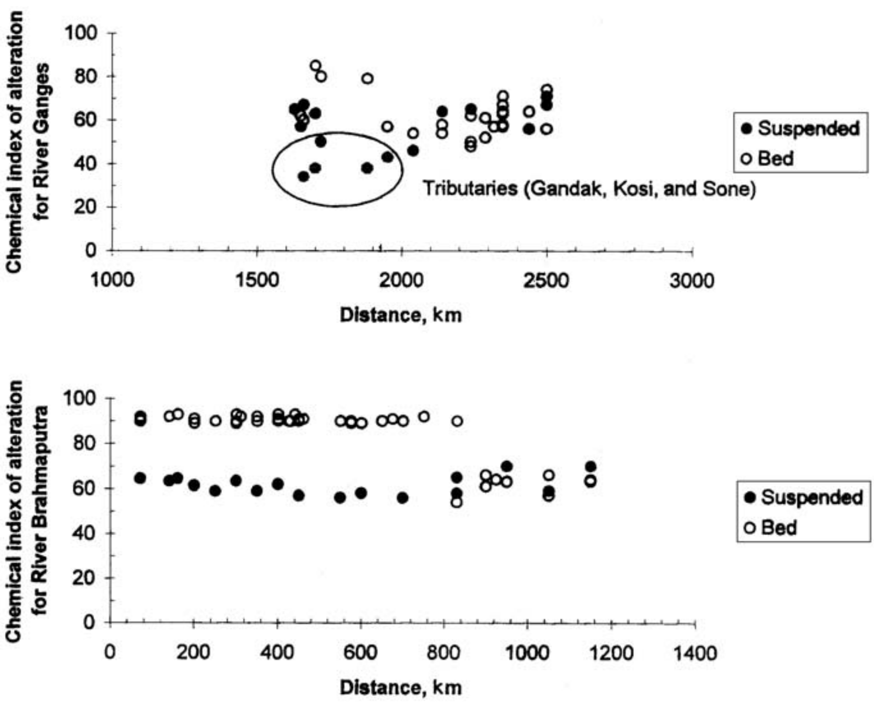

Figure 6.4 Water chemical data plotted in the silicate system
Source: Adapted from Garrels and Christ, 1965
Notes
Circled areas contain a large number of data and only a few mean values are indicated.

coarse grained, quartz dominates the mineralogy even in the suspended sediments, and in the estuarine region the proportion of quartz over feldspar depends on mean size and salinity (Subramanian and Jha, 1988).

Among the heavy minerals in the bed sediments, amphibole and epidote are present throughout the river basin; in the Megna sediments, metamorphic minerals such as kyanite are present in small quantities, whereas in the Ganges and Brahmaputra bed sediments, zircon and garnet are present. Small quantities of ilmanite and zircon are present only in very coarse fractions in all three river systems (Datta and Subramanian, 1998). Overall, the heavy mineral suite represents the residual coarse size of the sediment load, and indicates physical denudation in comparison to chemical weathering. The chemical erosion rates vary widely, from a high value of about 266 tonnes/km^2/yr near Patna for the Ganges to a low of about 90 tonnes/km^2/yr for the upper reaches of the Brahmaputra River in India. Both these values are far in excess of world average solute erosion rates (30 tonnes/km^2/yr). The average solute erosion rate for the Indian subcontinent is around 68 tonnes/km^2/yr (Datta and Subramanian, 1998). Thus the Himalayan drainage system transports the dissolved load at greater rates compared to many other major river basins in the world. The sediment load of the total river system is around 1 billion tonnes per year; assuming a density of 0.8 gm/cm^3 for sediments in suspension in the water column, an erosion rate of about 15.7 cm every 100 years can be calculated for the combined system. The Ganges gives a very low erosion rate at 2 cm/year, while the Brahmaputra gives a rate of about 4.1 cm/year. Abbas and Subramanian (1984) gave a sediment erosion rate of about 438 tonnes/km^2/yr at Calcutta and for the entire Ganges basin the erosion rate is about 622 tonnes/km^2/yr, while for the Brahmaputra basin the rate is 865 tonnes/km^2/yr. An average erosion value of about 600 tonnes/km^2/yr for the Himalayan river system can be arrived at after correcting for discharge variations in individual rivers. These values are far in excess of the global average of 150 tonnes/km^2/yr (Milliman and Meade, 1983). On the other hand, the sedimentation rate in the Ganges basin is around 6.2 mm/year, with extreme values of 2–9 mm/year at different tributaries in the basin, whereas in the Brahmaputra river system the deposition rates vary from 10 mm/year near the India-Tibet border to a low of 2 mm/year near the India-Bangladesh border (Subramanian and Ramanathan, 1996). In the mountain regions of Nepal with headwaters for a number of rivers, some of the small river beds are reported to be rising at the rate of about 15–30 cm/year (Valdiya, 1984). Goswami (1994) attributes the increase in erosion and sedimentation rates, even in the upper reaches of the Brahmaputra, to active seismic zones in the region. In the lower delta region, sedimentation rates are compounded by subsidence and the rate here is around 1.88 mm/year

(Hoque *et al.*, 1985); based on net radiocarbon dates of about 12,500 years for a 20-metre sediment core in the delta region (Umitsu, 1993), a net subsidence rate of about 2 mm/year can be arrived at for this region. Thus, in the lower reaches of the rivers as well as the upper reaches of the Brahmaputra, the sedimentation rate is a combination of sediment accumulation and subsidence.

Conclusions

The water chemistry of the Ganges and Brahmaputra does not show any specific local signature, so that even long-term data indicate their similarity with other large rivers in the world. Though the river water discharge is monsoon controlled, due to the large alluvial hinterland areas atmospheric contribution to the overall water chemistry is negligible for all parameters with the exception of Cl^{-1}. CIA values (Figure 6.5) show

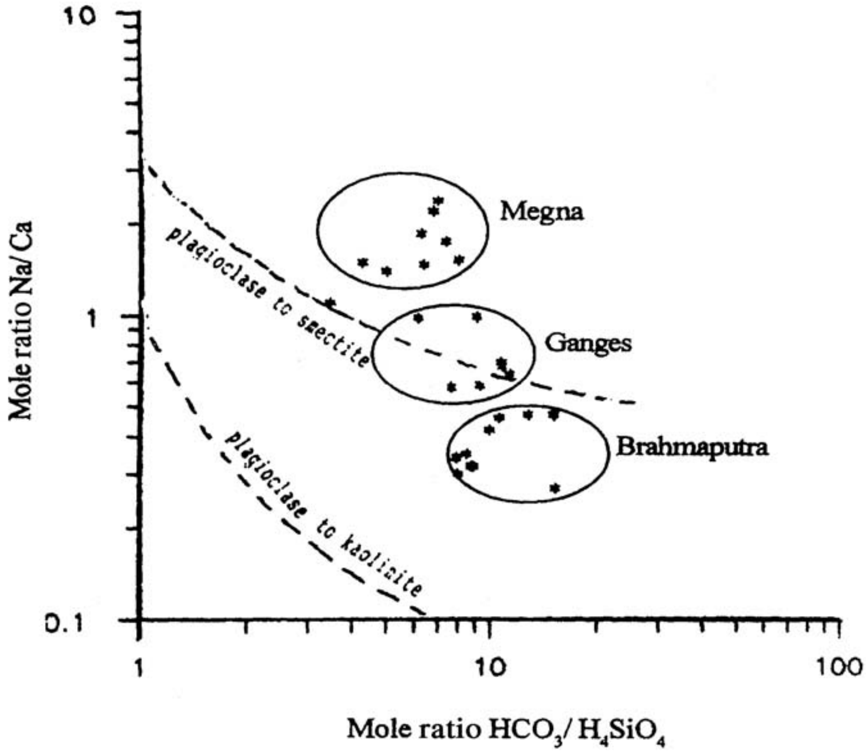

Figure 6.5 Chemical index of alteration (CIA)
Source: Adapted from Nesbitt and Young, 1982
Note
Values for Himalayan river system at various locations.

wide variations: these are high (85 and above) near the multi-river region of Patna; at other places, the values are less than 65 for the Ganges. Brahmaputra sediments generally show very high CIA values. Heavy mineral assemblages in the bed sediments for both river systems broadly reflect a strong physical weathering component. The large sediment load masks any signature of possible chemical interaction between water and sediments. Sediment erosion and accumulation rates in these river basins reflect a combination of present hydrological and long-term tectonic processes.

REFERENCES

Abbas, N. and V. Subramanian. 1984. "Erosion and sediment transport in the Ganges river basin (India)", *Journal of Hydrology*, Vol. 69, pp. 173–182.

Ahmed, K. M. U. 1994. "The hydrogeology of the Dupi Tila Sands aquifer of the Barind Tract, NW Bangladesh", PhD thesis, University of London.

APHA. 1995. *Standard Methods for the Examination of Water and Waste Water*, 19th edn. Washington, DC: American Public Health Association.

Biksham, G. and V. Subramanian. 1988. "Nature of solute transport in the Godavari river basin, India", *Journal of Hydrology*, Vol. 103, pp. 375–392.

Das, D. K. 1988. "Chemistry of monsoon rains over Calcutta, West Bengal", *Mausam*, Vol. 39, pp. 75–82.

Datta, D. K. and V. Subramanian. 1997. "Nature of solute load in the rivers of Bengal basin, Bangladesh", *Journal of Hydrology*, Vol. 198, pp. 196–208.

Datta, D. K. and V. Subramanian. 1998. "Distribution and fractionation of heavy metals in the surface sediments of the Ganges-Brahmaputra-Megna river system in the Bengal basin", *Environmental Geology*, Vol. 36, Nos 1/2, pp. 93–101.

Depetris, P. J. and J. L. Probst. 1998. "Variability of the chemical index of alteration (CIA) in the Parana River suspended load", *Mineralogical Magazine*, No. 62A, pp. 366–367.

Garrels, R. M. and C. L. Christ. 1965. *Solutions, Minerals, and Equilibria*. New York: Harper, p. 450.

Gibbs, R. J. 1970. "Mechanisms controlling world water chemistry", *Science*, No. 170, pp. 1088–1090.

Goswami, D. C. 1994. "Brahmaputra River, Assam, India: Physiography, basin denudation and channel aggradation", *Water Resources Research*, Vol. 21, No. 7, pp. 959–978.

Handa, B. K. 1968. "Chemical composition of rain water in some parts of northern India: Preliminary studies", *Indian Journal of Meteorology and Geophysics*, Vol. 19, pp. 175–180.

Hoque, M. J., M. A. Khan, I. Shamsuddin, and Shahedul. 1985. "Land accretion and land reclamation of the coastal areas of Bangladesh in development of coastal areas of Bangladesh", Bangladesh Planning Commission Report, pp. 17–23.

Meybeck, M. 1983. ‘‘Atmospheric inputs and river transport of dissolved substances’’, in B. W. Webb (ed.) *Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships*, Proceedings of Hamburg Symposium. IAHS Publication 141, pp. 173–191.

Milliman, J. D. and R. H. Meade. 1983. ‘‘Worldwide delivery of sediment to the oceans’’, *Journal of Geology*, Vol. 91, pp. 1–21.

Mukherjee, A. K., K. Nand, B. Mukhopadhyay, and S. G. Chanekar. 1986. ‘‘Rainwater chemistry over Indian sea areas during monsoon seasons’’, *Mausam*, Vol. 37, pp. 173–178.

Mukhopadhyay, B., S. V. Datar, and H. N. Srivastava. 1992. ‘‘Precipitation chemistry over the Indian region’’, *Mausam*, Vol. 43, pp. 249–258.

Nesbitt, H. W. and G. M. Young. 1982. ‘‘Early Proterozoic climates and plate motions inferred from major element chemistry of lutites’’, *Nature*, No. 299, pp. 715–717.

Nijampurkar, V. N., M. M. Sarin, and D. K. Rao. 1993. ‘‘Chemical composition of snow and ice from Chhota Shingri glacier, Central Himalaya’’, *Journal of Hydrology*, Vol. 151, pp. 19–34.

Sarin, M. M., S. Krishnaswami, K. Dilli, B. L. K. Somayajulu, and W. S. Moore. 1989. ‘‘Major ion chemistry of the Ganges-Brahmaputra river system – Weathering processes and fluxes to the Bay of Bengal’’, *Geochimica et Cosmochimica Acta*, Vol. 53, pp. 997–1009.

Sequeira, R. and D. Kelkar. 1978. ‘‘Geochemical implications of summer monsoonal rainwater composition over India’’, *Journal of Applied Meteorology*, Vol. 17, pp. 1390–1396.

Stallard, R. F. and J. M. Edmond. 1981. ‘‘Geochemistry of the Amazon: Precipitation chemistry and the marine contribution to the dissolved load at the time of peak discharge’’, *Geophysical Research*, Vol. 86, pp. 9844–9858.

Subramanian, V. and P. K. Jha. 1988. ‘‘Geochemical studies on the Hooghly (Ganges) estuary’’, in E. T. Degens, S. Kempe, and A. S. Naidu (eds) *Transport of Carbon and Minerals in Major World Rivers, Lakes and Estuaries*, Part 5. Hamburg: SCOPE/UNEP Sonderband, Mitteilungen aus dem Geologisch-Palaontologischen Institut, University of Hamburg, pp. 267–283.

Subramanian, V. and A. L. Ramanathan. 1996. ‘‘Nature of sediment load in the Ganga-Brahmaputra river system in India’’, in J. D. Milliman and B. K. Haque (eds) *Sea Level Rise and Coastal Subsidence*. Amsterdam: Kluwer Academic Publishers, pp. 226–245.

Subramanian, V., L. Van t’Dack, and R. Van Grieken. 1985. ‘‘Chemical composition of river sediments from the Indian sub-continent’’, *Chemical Geology*, Vol. 48, pp. 271–279.

Umitsu, M. 1993. ‘‘Late Quaternary sedimentary environments and land forms in the Ganges delta’’, *Sedimentation Geology*, Vol. 83, pp. 177–186.

Valdiya, K. S. 1984. *Aspects of Tectonics – Focus on South-Central Asia*. New Delhi: Tata McGraw-Hill.

7

Modern water level and sediment accumulation changes of Lake Abaya, southern Ethiopia – A case study from the Bilate River delta, northern lake area

Brigitta Schütt and Stefan Thiemann

Introduction

Since recording started, water levels in Lake Abaya, a lake of the southern main Ethiopian Rift Valley, have been subject to repeated changes. But since the early 1990s, water levels in Lake Abaya have continuously increased (Seleshi Bekele, 2001). Climatic conditions – probably one of the most important factors influencing regional water budget and thus lake level – have shown high variability over the past 50 years, but lack any trend. Thus, according to results of climate data analysis, climatic conditions as the only factor influencing lake-level changes have to be excluded.

Additionally, when analysing Lake Abaya's lake-level changes it has to be considered that since the 1970s dramatic population growth, changes in land ownership, clearing of forests and bushland, and changes in cultivation manners have caused increasing soil erosion processes. As a consequence of this, the sediment yield of the Lake Abaya tributaries also increased. As Lake Abaya is of only shallow depth (maximum depth 26 m), its lake level reacts quite sensitively to changes in input factors, and it is likely that increased sediment intake significantly influences basin bathymetry and thus basin volume. Therefore, Lake Abaya is an ideal subject for the analysis of complex patterns of climatic and human impacts on lake-level changes. However, as Lake Abaya is located in the main Ethiopian Rift Valley, one of the most active tectonic zones of the earth, the influence of neo-tectonics at the southern sill also has to be kept in mind as a factor influencing lake-level fluctuations.

To assess the processes of soil erosion as a factor modifying basin volume, sediment cores were extracted from the lake centre and the deltas of the major tributaries. The variation in intensity of man's impact on erosion and accumulation processes is pointed out by investigaton of subaqueous relief, volume of accumumulation bodies, and character of lacustrine and fluvio-lacustrine sediments. In this study, sample results are shown for northern Lake Abaya where the Bilate River deposits its sediments.

Study site

The Lake Abaya-Lake Chamo system is a graben fill in the southern section of the main Ethiopian Rift Valley. A sill covered by swampy forestland of approximately 1 km width separates Lake Abaya from the adjoining Lake Chamo in the south. The altitude difference between the lakes is about 70 m (Lake Abaya is approximately 1,188 m above sea level; Lake Chamo is approximately 1,118 m above sea level). Altogether, drainage of the Lake Abaya-Lake Chamo system covers a watershed of approximately 18,600 km^2, while the lake areas cover approximately 1,550 km^2. As Lake Abaya lacks a direct outflow and dispenses water only by overflowing the sill in the south which separates Lake Abaya from Lake Chamo, Lake Abaya can be characterized as a quasi-endorheic basin. According to this, the possible influence of neo-tectonics on lake-level changes also has to be considered.

Most recently, the water of Lake Abaya has been of a reddish-brown colour due to the silty to clayey sediments transported into the lake by its tributaries. Lake Abaya is fed by the major drainage systems of the Bilate River from the north, the Gidabo and Gelana Rivers from the east, and in the west by the Hare, Hamessa, and Baso Rivers. The catchment of the Bilate River is the biggest of the Lake Abaya tributaries, draining 5,754 km^2. High sediment yields of the tributaries cause deposition of extended alluvial fans at the base of the Rift Valley flanks, continuing as deltas into the lake (Figure 7.1). The limnic environment of Lake Abaya is slightly basic (pH 9.0–9.3) with low salinity (950–1,050 µS), and corresponds to a typical tropical lake environment, lacking complete lake circulation.

Climatic conditions in the drainage basin are subhumid and vary between a tropical climate in the Rift Valley region and a temperate climate in the highlands, in both cases characterized by two annual rainy seasons and a distinctive arid period in winter. Annual as well as monthly

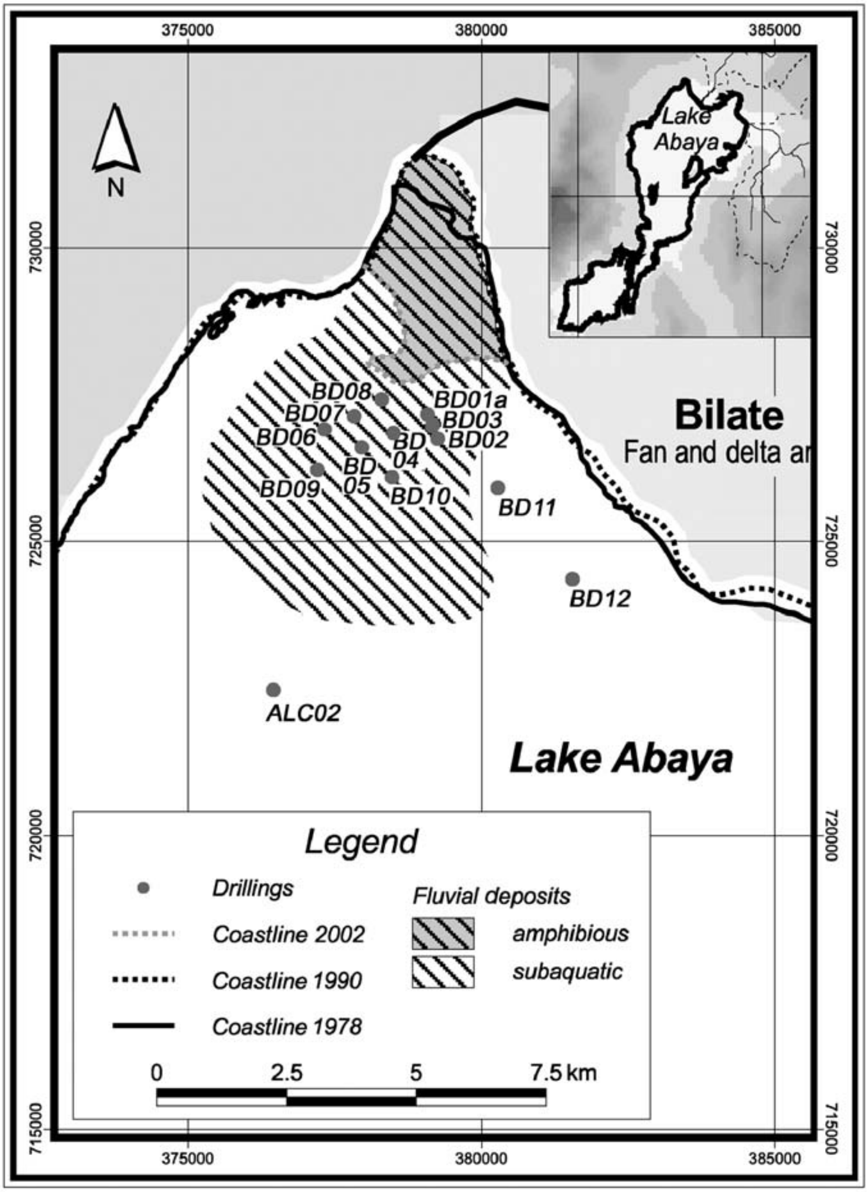

Figure 7.1 Map of Lake Abaya showing the lake's bathymetry, drainage basin topography, and distribution of major areas of fan deposits

Map 1:250,000, sheet Abaya, 1984

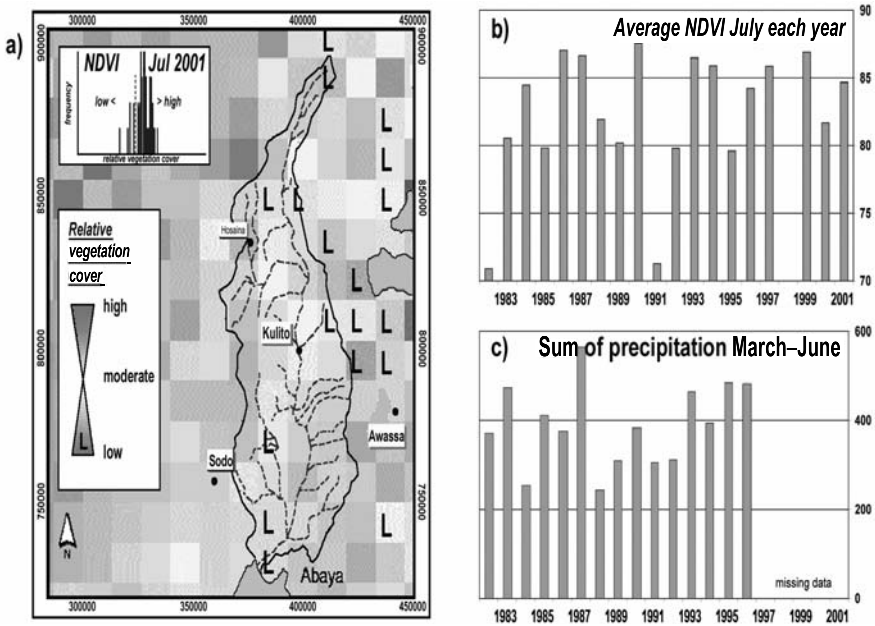

Figure 7.2 Time series analysis of monthly NDVI in the Bilate River catchment

sums of precipitation are highly variable (Figure 7.2), but do not show a significant trend over the past 20 years. In contrast, time series analysis of the annual discharge of the Bilate River (Figure 7.3) shows negative trends for most of the drainage basins tributary to Lake Abaya (11 gauging stations, covering almost 46 per cent of the Lake Abaya drainage; the gauging period in some places started in the 1970s). At the same time, the growing population in the area, with approximately 5 per cent annual increase since 1970, has caused a doubling of water consumpion (Seleshi Bekele, 2001).

Methods

Expansion of the Lake Abaya surface area can be recorded for the time period since 1965 by image analysis such as panchromatic air photographs, CORONA images, and Landsat TM images. Following this, datasets available since 1981 from AVHRR-NOAA (advanced very high

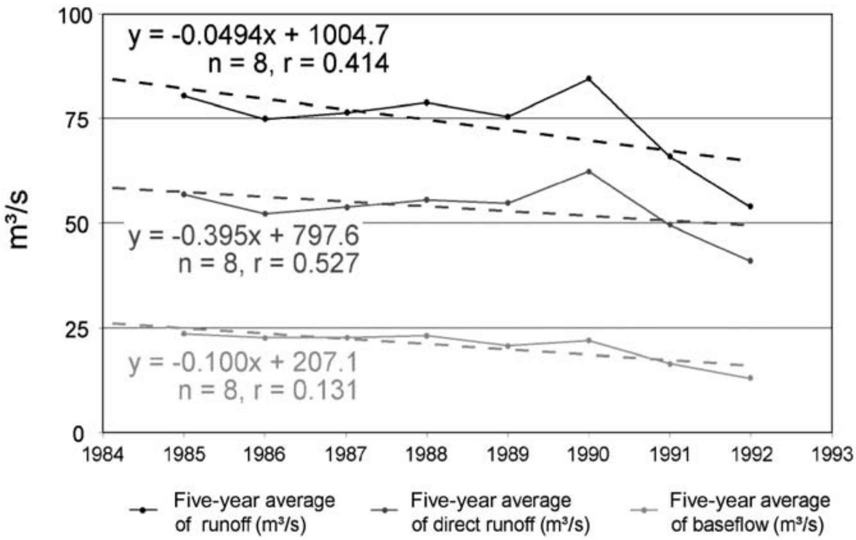

Figure 7.3 Bilate River, Tena Bilate station: Five-year running average of runoff and the different discharge components; gauging period 1983–1992

resolution radiator – National Ocean and Atmosphere Administration) were used to record vegetation cover on a monthly basis by the NDVI (Normalized Digital Vegetation Index) (Gregor, Schütt, and Förch, 2004). Results shown here are based on monthly average NDVI data provided by the Global Ecosystem Database with an $8 * 8$ km^2 grid size. Coastlines were obtained from topographic maps scaled 1:50,000 and 1:250,000, edited in 1990 and 1979. Most recent coastlines were measured by boat using a GPS (global positioning system).

Undisturbed lacustrine sediments were taken using a coring plumb line (Figure 7.4). Analysis of sediments as a first step used a description of depositional units to identify stratigraphical units (colour, lamination, sedimentary structure). Preparation of samples started by drying them at 50°C in a drying cabinet and homogenizing them in an agate swing-sledge mill. Organic carbon contents were determined by an infrared cell in a LECO high-frequency induction oven (detection limit = 0.02 mass % C). Analysis of mineralogical compounds was carried out by X-ray powder diffraction analysis using a copper k_a-tube (Siemens DIFFRAC AT/D5000). Contents of mineral components were recorded as volume-percentage by the intensity of diffraction at the mineral's major diffraction peak (cps – counts per second) relative to the intensity of quartz at its major diffraction peak (d_{101}). To identify composition of clay minerals, disaggregated samples were prepared as oriented mounts. Mounts were

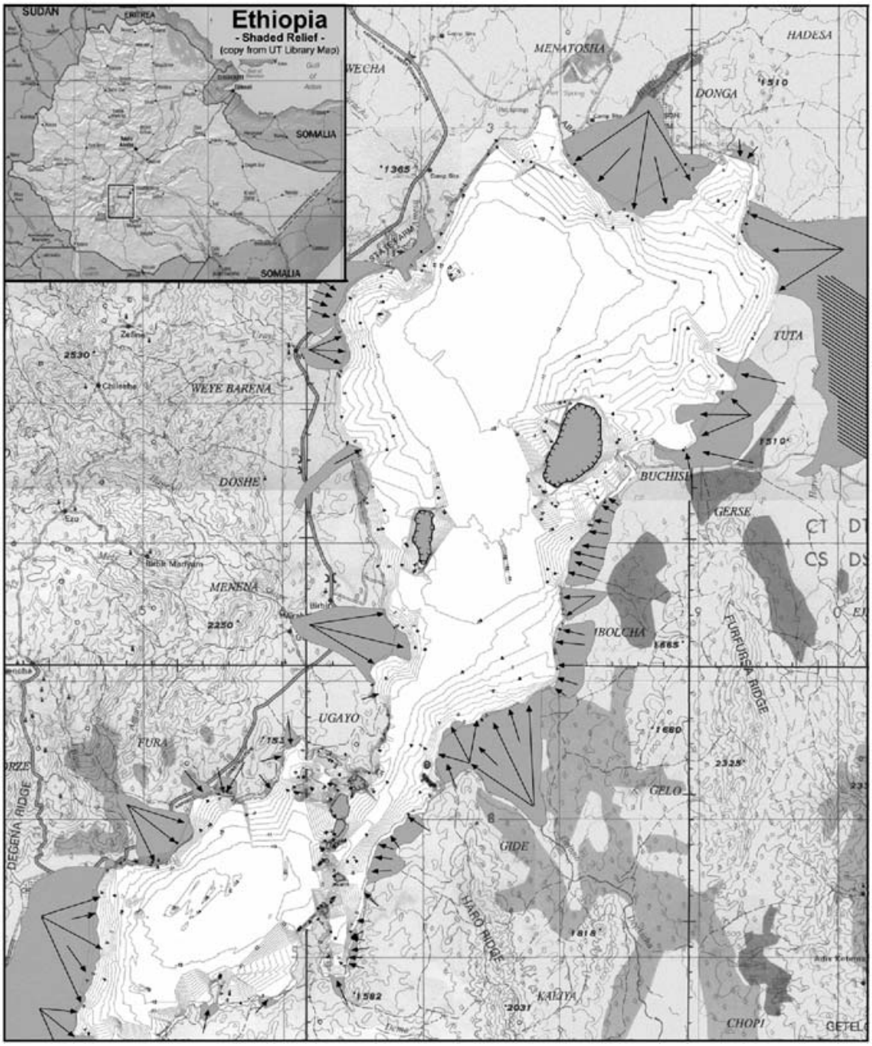

Figure 7.4 Map of northern Lake Abaya, showing location of drillings and running of most recent coastlines in the delta areas

measured air-dried and after treatment with ethylene glycol and heating up to 550°C, and each mount was X-rayed for 2–30 .q°2.

Due to the young age of the sediments (<50 years), conventional dating techniques are not reliable. As in the area of interest pesticides containing persistent organic pollutants such as DDT and Aldrin are still used, contents of DDT and Aldrin and its derivates are used for age detection; these analyses are still in progress.

Results

Time series analysis of NDVI

Spatial distribution of NDVI data in the Bilate basin distinctly points to differences in development of vegetation due to precipitation and topography. The eastern exposed flanks of the Rift Valley, which correspond to the western part of the Bilate drainage, are affected by orographic precipitation. Thus, vegetation cover here is denser than in the Rift Valley itself and its western exposed flank. This pattern is also reflected in seasonal variations of NDVI, such as shown for average NDVI in the Bilate drainage for July 2001, representing vegetation cover for the end of the vegetation period (Figure 7.2a). Time series analysis of average July NDVI of the Bilate drainage (Figure 7.2b) shows high variability but lacks a trend. Comparison of these data with the sum of precipitation over the four previous months (March–June; Figure 7.2c) indicates dependency between weather and vegetation cover. It is expected that correlations shown will get closer when analysing weather conditions.

Lake-level changes and shoreline shift

Analysis of the monthly lake-level data from Lake Abaya shows, after a spill in the second half of the 1970s, oscillating lake levels with an altogether lower mean lake level until 1992. After the lake-level low in the second half of 1992, lake levels increased steadily, portraying seasonal variations in precipitation (Figure 7.5).

Beneath lake levels, runoff data of the largest tributaries of Lake Abaya are available, but vary in gauging periods. Also here monthly discharge data reflect seasonal variations in precipitation, whereas increasing discharge data since 1992 such as recorded for the lake levels are missing (Figure 7.6). In addition, for the Bilate River at the Tena Bilate gauging station, located just above the fan deposits in the lower course of the Bilate River, runoff data were analysed. Based on the five-year running average of runoff (m^3/s), the different discharge components for the gauging period from 1983 until 1992 were calculated. Trend analysis of the resulting data shows distinct negative trends for the total runoff as well as for runoff originating from baseflow and direct runoff (Figure 7.3). Additionally, calculation of the baseflow as a percentage of the total runoff trend line shows a coefficient of $b = -0.905$ ($r^2 = 0.873$), which

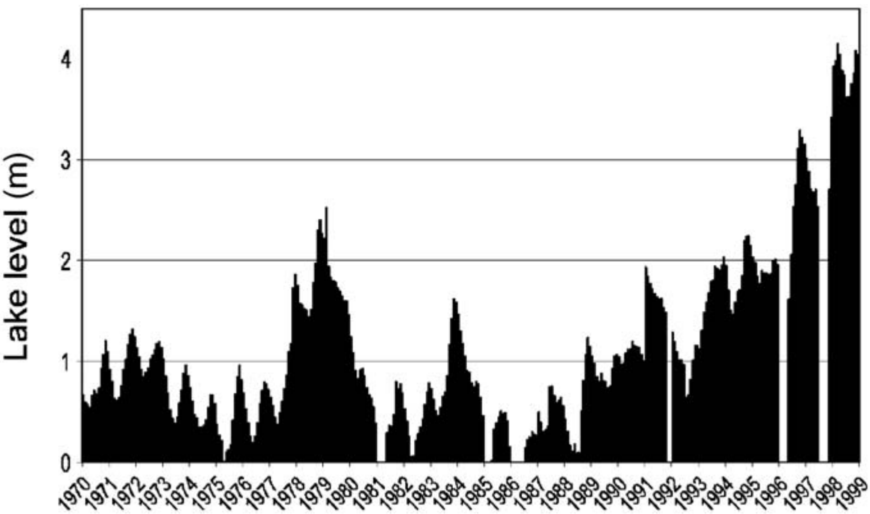

Figure 7.5 Monthly lake water levels of Abaya Lake at Arba Minch gauging station

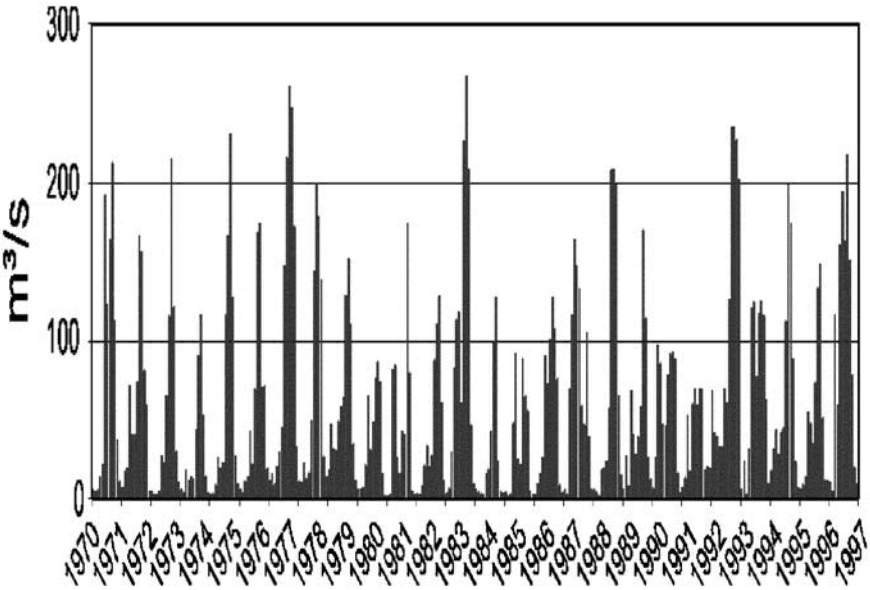

Figure 7.6 Bilate River at Abaya Outlet station: Maximum monthly discharge; gauging period 1971–1996

points out that baseflow decreases stronger than direct runoff (Figure 7.3).

Since the early 1950s the area of the Bilate delta has been irrigated and used for growing cash crops (cotton, *tabak*) by setting up a state farm (Bilate State Farm). One of the most recent mouths of the Bilate River is located in a bay at the western fringe of the fan and delta area of the river. Shorelines moved back during a low-lake-level period in the 1980s (Figure 7.4). Beyond this, survey of the shoreline from February 2002 points out that the most recent Bilate delta is continously growing, causing penetration of the shoreline into the lake.

Sediment analysis

In the Bilate delta area altogether 12 cores were extracted covering the area of most recent fluvio-lacustrine sedimentation (Figure 7.4). All sediments extracted are finely laminated, changing between brownish, dark, and light greyish colours. Grain size of these sediments is clay with frequently occurring silty components. Sediments are soft and only poorly consolidated. At the base of the sediments extracted in all cases highly compacted sandy sediments prevented deeper penetration of the coring plumb line.

Graphs of organic carbon content for the sediments extracted from the Bilate delta show related shapes (Figure 7.7): Below the lake floor organic carbon content in general decreases; but within a few centimetres' depth the sediment's organic carbon contents increase again. In the sediments extracted close to the mouth of the Bilate River this characteristic appears before 10 cm depth is reached, while in the sediments extracted from the delta's margin the increase of organic carbon contents starts at 10–15 cm depth. In core BD08, extracted in front of the Bilate mouth, there are only 17 cm of clayey sediments before consolidated sandy layers start. The temporal resolution given from fluvio-lacustrine sediments is reduced. In contrast, sediments extracted from the delta's margin reach down to 40 cm depth, and therefore go farther back into sedimentation history. In drillings BD02, BD04, and BD07, extracted from the central part of the Bilate delta, after the increase of organic carbon content at 10–15 cm depth values remain more or less stagnant before they distinctly increase at 20–25 cm depth in the sediments of BD02 and BD04 and at 18 cm depth in BD07. The overall shape of the organic carbon content graphs can also be traced in drillings BD05, BD06, and BD10, all extracted from the margin of the delta, but at least a distinct downward decrease of organic carbon contents is missing (Figure 7.7).

Next to organic carbon content, lake sediments were investigated for their overall mineralogical composition (Figure 7.8). Using the composi-

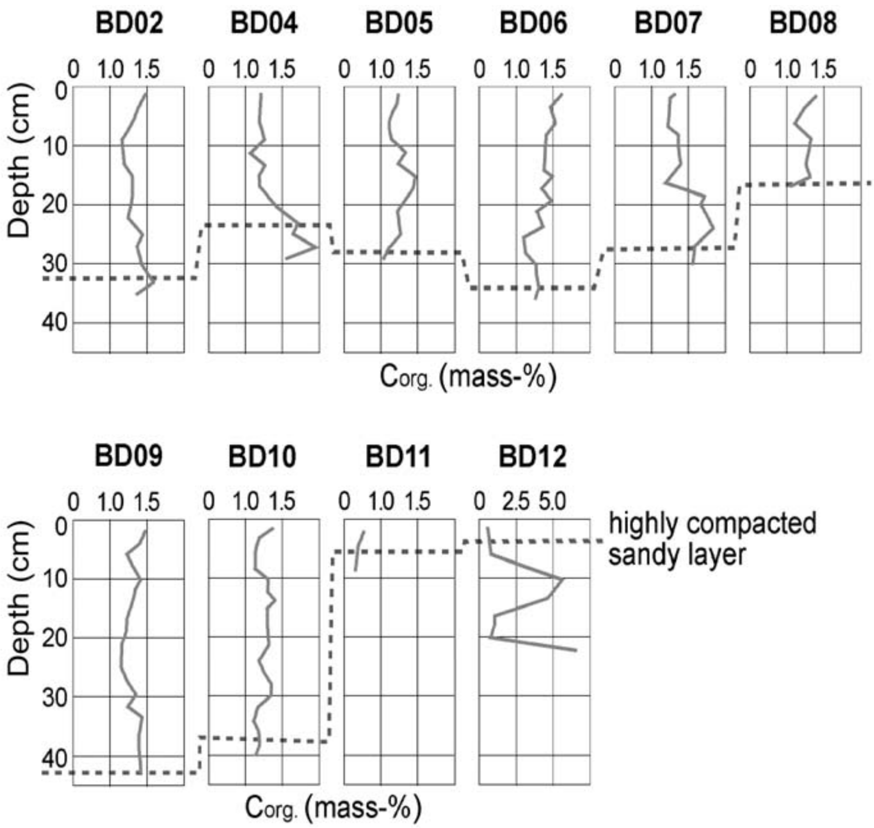

Figure 7.7 Organic carbon content in the fluvio-lacustrine sediments extracted from the Bilate delta area

tion of some selected minerals of drilling BD05 as an example of the other drillings, it becomes clear that the run of graphs is only poorly connected. Quartz and sanidine are the major mineralogical composites, complemented by augite, analcime, mica, biotite, muscovite, and montbrayite – all components which point out the origin of the sediments from a drainage basin with bedrock formed by volcanic processes. Furthermore, pedogenic minerals (iron and aluminium oxides, clay minerals) constitute up to 10 per cent by volume of the mineralogical composition. While iron oxides are dominated by goethite, next to kaolinite the three-layer clay mineral montmorillionite predominates in the composition of clay minerals.

Integrating all sediments extracted in the Bilate delta area (n = 150) into a statistical analysis it can be pointed out that:

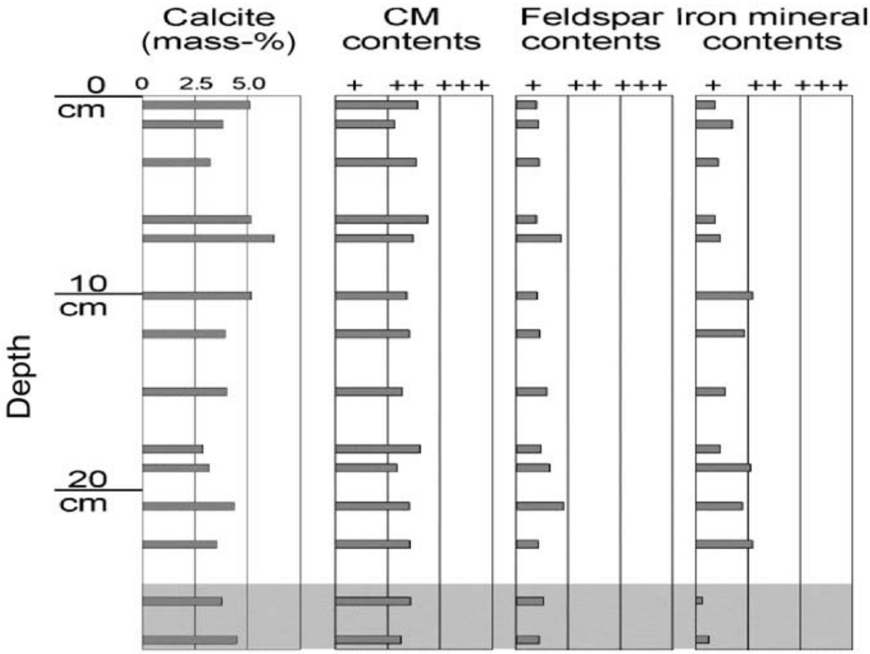

Figure 7.8 Mineralogical composition of drilling BD05 from the Bilate delta

- oxide contents such as boehmite, hematite, and goethite are always positively correlated with each other ($\alpha < 0.001$)
- oxide contents are always positively correlated with clay mineral contents ($\alpha < 0.001$)
- carbonate contents (calcite, dolomite) are always positively correlated with the clay mineral contents ($\alpha < 0.001$) as well as with the oxide contents ($\alpha < 0.001$)
- quartz and sanidine contents as well as contents of augite, analcime, mica, and montbrayite are positively correlated with each other ($\alpha < 0.05$) and at the same time are negatively correlated to the minerals of the carbonate group, the oxide group, and the clay mineral group ($\alpha < 0.001$).

Discussion

Lake-level fluctuations of endorheic basins are among the best indicators of climatic fluctuations during the Holocene, determined by relief, geology, soils, vegetation, and paleohydrology of their watersheds as the main factors (Street-Perrott, 1980). The magnitude and frequency of lake-level fluctuations can be reconstructed from geomorphological and sedimentological analyses (e.g. beach ridges, beach terraces, cliff edges, lacustrine and fluvio-lacustrine sediments) in conjunction with knowledge of the present-day water balance of the lake (Street-Perrott and Harrison, 1985). Apart from the deposition of detritus originating from the drainage basin (allothigen), lacustrine sediments are characterized by precipitation of minerals from aqueous solutions (authigenic). Because this process is substantially influenced by lake water salinity and its chemical composition, such sediments are particularly of interest for the reconstruction of the paleolimnic environments. For this purpose the character of carbonates of lacustrine sediments is of interest to obtain information about the paleoenvironment of the lake itself during deposition of the lacustrine sediments. By contrast, composition of minerals such as iron oxides or clay minerals formed by soil-forming processes in the drainage basin area gives information about the environmental conditions in the drainage basin before deposition of the lacustrine sediments (Schütt, 1998).

Water balance in the drainage basin area

The environmental conditions in the Lake Abaya catchment concerning the overall water balance can be summarized as follows. Since 1992 the water level of Lake Abaya has constantly increased. During the same period of time annual precipitation in the Lake Abaya catchment has been of high variability, but does not show any significant trend. Sums of the annual outflow of the major Lake Abaya tributaries since the 1970s predominantly remain stagnant or even show a negative trend. Simultaneously, the share of baseflow forming total runoff – as demonstrated for the Bilate River in this chapter – constantly decreases.

Time series analysis of the lake-level data shows that after the spill in the second half of the 1970s Lake Abaya's water level constantly decreased until 1988. After 1988 the lake system refilled again and until 1992 oscillated within well-known margins. Since 1992 in southern Ethiopia some very wet years have occurred, which have possibly have been associated with El Niño and which caused a significant rise in the water level (ENSO – El Niño/Southern Oscillation – events at the end of 1991 and 1998; Anyamba and Eastman, 1996). Under natural conditions in subhumid climates during humid phases the vegetation cover obstructs surface runoff and erosion, and infiltration rates are increased (Horton, 1945). As conditions are reversed during arid phases, surface runoff increases and infiltration rates and subsurface flow are reduced (Dunne, Zhang, and Aubry, 1991; Rogers and Schumm, 1991). The same effect is due to erosion and soil erosion processes: where vegetation cover is removed, disturbance of the soil structure as well as the removal of canopy cover, protecting the soil against splash effects, and removal of attaching root systems favour surface runoff and impede infiltration (Richter, 1976; Dunne, Zhang, and Aubry, 1991; Rogers and Schumm, 1991). Thus it can be concluded that the decreasing contribution of baseflow to runoff generation is due to decreasing infiltration rates as a reaction to changes in vegetation cover and land use. The negative trend in runoff generation (gauging station Tena Bilate) while precipitation data lack any trend might be caused by changes in water consumption in the Bilate catchment area in the recent past. Thus, alongside the natural and quasi-natural influences on water balance, possible increasing direct human impact by water consumption, including domestic water use and water use for irrigation and livestock, has to be considered for the Lake Abaya drainage basin. It is assumed that water consumption is steadily increasing due to increasing population numbers. Domestic use, however, is limited, since the average consumption in rural Ethiopia is well below 20 litres per person per day. Irrigation water demand has been increasing because of large-scale cash-crop production on several state farms in the drainage basin (in former times growing mainly cotton, today preferably maize). It can be concluded that water consumption was not a major factor for the lake water balance over recent years; but it can be expected that the extremely high population growth (average growth rates of 2.23 per cent of rural and 4.11 per cent of urban populations) will show its effects very soon (CSA, 1998).

Summarizing, it should be pointed out that a direct interrelation between inflow from tributaries and lake-level changes cannot be stated.

Organic carbon content

Organic carbon in lacustrine sediments can be deposited as detritus due to erosion processes in the catchment (Dunne, Zhang, and Aubry, 1991). Additionally, limnic biomass production is an important source of organic carbon in lacustrine sediments (Vallentyne, 1962). Limnic biomass production is highly dependent on availability of nutrients and light, and therefore is reduced when high concentrations of suspended load cause high turbidity (Evans and Kirkland, 1988).

Different processes of decomposition and preservation affect organic matter in the limnic environment. During the process of deposition autochthonous as well as allochthonous organic matter gets decomposed by early diagenitic decomposition (Meyers and Ishiwatari, 1993). Early diagenitic decomposition occurs in both the aerobic and anaerobal limnic environment and, in general, under natural conditions can result in the total decay of organic matter (Livingstone, 1984). In general, organic carbon contents in the lacustrine sediments are very low and decrease in concentration from top to bottom, suggesting a progressively early diagenetic decomposition of organic matter (Rheinheimer, 1974). Thus increased organic carbon contents of lacustrine sediments indicate deposition rates higher than those caused by soil erosion processes (Lerman, 1979). In lacustrine environments affected directly by fluvial processes, as shown for the delta area of the Bilate River, oscillations of the sediment's organic carbon concentrations might reflect deposition of soil sediments from different horizons (topsoil is rich in organic carbon; subsoil is poor in organic carbon). Thus it can be concluded that varying concentrations of organic carbon content in the sediments extracted reflect the soil erosion processes in the most recent past, starting with deposition of organic-rich topsoil in the underlying layers (BD02, BD04, BD07) (Dunne, Zhang, and Aubry, 1991; Richter, 1976). Additionally it has to be considered that the subaqueous currents of inflowing surface runoff might vary in location and velocity, causing changes in concentration of the sediment's organic matter.

Mineralogical composition

Apart from allochthonous detritus, authigenic carbonates, sulphates, and chlorides make up the mineralogical composition of lacustrine sediments. Detritals originate from decomposition of bedrock in the drainage basin and reflect the mineral fabric of the bedrock (i.e. quartz, sanidine, feldspar) and predominating soil-forming processes (pedogenic minerals such as clay minerals, hematite, goethite, boehmite). Early diagenetic processes, controlled by salinity and the chemistry of the lake water, can modify the mineralogical properties, especially those of authigenic and pedogenic minerals.

Carbonates

Calcites and dolomites are the only carbonates detected in the lacustrine sediments extracted. As the occurrence of limestone in the drainage area of Lake Abaya is unknown, it has to be concluded that the calcites found are authigenic. Essentially, the autochthonous development of calcareous mud (automicrite), which is the predominant form of carbonate deposits in the lacustrine sediments of Lake Abaya, is due to water chemistry changes effected by decomposition of organic matter, biological assimilation of CO_2, or temperature increases with consequential salinity deviations (Flügel, 1978). Warming of the water body in summer and evaporation can also lead to deposition of carbonates, especially in shallow water areas (Schäfer, 1972). Low dolomite contents in the lacustrine sediments correspond to restricted processes of early diagenetic dolomitization which are due to the low concentrations of magnesium ions in the limnic environment (Folk and Landes, 1975).

As limestones are not likely in the Lake Abaya drainage area, the predominant source of calcium bound in the calcites is the weathering products of feldspars (i.e. sanidine $K_{0.42}Na_{0.58}Ca_{0.03}AlSi_3O_8$), which originate from magmatic processes with acid fusion ($SiO_2 > 65$ mass percentage) (Dear, Howie, and Zussman, 1992). In general, feldspars can easily be weathered, with the earth and alkaline earth metals mobilized and transported away as solutes and the remaining Al and Si ions forming clay minerals. Statistical analysis of mineral components shows that the higher the clay mineral contents in the lacustrine sediments, the more the carbonate contents increase while contents of geogenic detritals like feldspar and quartz decrease. Thus, the statistical analysis confirms the origin of Ca ions bonded in the carbonates as well as the formation of clay minerals from weathering of feldspars.

Pedogenic minerals

Clay minerals are generated in the drainage basin as a consequence of chemical weathering and soil-forming processes. While in acid environments clay minerals get disturbed (Ulrich, 1981), in slightly basic and saline environments three-layered clay minerals get meta-stabile and their illitization might occur (Heim, 1990).

Also hematite (Fe_2O_3) develops as a consequence of weathering and soil-forming processes, predominantly under tropical and subtropical climatic conditions with high temperatures and negative soil water balance, by dehydration of ferrihydrates ($5Fe_2O_3{\cdot}9H_2O$) (Schwertmann and Taylor, 1989). In lacustrine environments under reducing FeOOH conditions hematites are meta-stabile and form goethite (Macedo and Bryant, 1989).

In the sediments from Lake Abaya a positive correlation between hematite and clay mineral contents points out their common origin from erosion of soils (Rohdenburg and Sabelberg, 1973). The same relation is underlined by the negative trend between contents of pedogenic minerals and the primary minerals quartz and feldspar: the higher the degree of weathering of the soil sediments the higher the contents of pedogenic-generated clay minerals and the lower the contents of unweathered primary minerals (Krauskopf, 1956).

Conclusions

Concentrations of detrital organic carbon as well as those of pedogenic minerals in lacustrine sediments are useful indicators for assessing intensity of erosion and soil erosion processes in the catchment and the state of the soils eroded. The altogether high concentrations of pedogenic minerals in the lacustrine sediments from Lake Abaya (Bilate delta) point to soil erosion, and especially the intensified erosion process due to human impact, as the predominating morphodynamics in the catchment of the Bilate River in the most recent past. Distinct decreases of organic carbon concentrations and of pedogenic minerals in the most recent sediments of the delta deposits show that either a distinct change in processes, such as a reduction of soil erosion intensity, or a distinct change in parent material, such as erosion of more poorly developed soils and soil horizons for example in areas highly degraded, occurred.

Due to the young age of the fluvio-lacustrine sediments exact dating is not possible. However, analysis of POPs shows that deposition of the delta deposits took place after 1939 (Schütt, Thiemann, and Wenclawiak, in press). As a more detailed temporal assignment is not possible with the state-of-the-art techniques, an accurate correlation of single strata to certain climatic (e.g. rainstorms) or historical (e.g. land reform) events is not possible. Correspondingly, quoting accumulation rates is yet not possible. Nevertheless, the run of graphs for mineralogical composition (Figure 7.8) points out that mineral and chemical components of lake deposits are a feasible tool to determine the volume of the strata over an extended area independent from facies (lacustrine/fluvio-lacustrine). Comparison of topographical maps and air photographs shows that since 1965 the Bilate River has deposited a delta area of approx. 5.5 km^2 at the western fringe of the ''old'' Bilate delta, which is an amphibian area today. From bathymetric measurements (Seleshi Bekele, 2001) an average sediment depth of 200 cm is estimated for this area – thus sediment volume of the amphibious area totals about $11 * 10^6$ m^3. However, the inundated area of the delta is approximately three times larger than the amphibious part: lakewards of the amphibian area, deposition of fluvio-lacustrine sediments covers approximately another 15–16 km^2. It is assumed that here the clayey, unconsolidated sediments found on top of the consolidated sandy strata are derived from soil erosion processes. Supposing an average depth of 25–30 cm for these uppermost strata, the volume of the most recently deposited delta sediments amounts to 4.0–$4.5 * 10^6$ m^3. Due to the extension history of the amphibious delta area it is assumed that the majority of the most recent delta sediments of the western Bilate fan were deposited since 1980.

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REFERENCES

Anyamba, A. and J. R. Eastman. 1996. ''Interannual variability of NDVI over Africa and its relation to El Niño/Southern Oscillation'', *International Journal of Remote Sensing*, Vol. 17, No. 13, pp. 2533–2548.

CSA (Central Statistical Authority). 1998. *The 1994 Population and Housing Census of Ethiopia. Results for Southern Nations and Nationalities People's Region*, Vol. II. Addis Ababa: CSA.

Dear, W. S., R. A. Howie, and J. Zussman. 1992. *An Introduction to the Rock-forming Minerals*. New York: Longman.

Dunne, T., W. Zhang, and B. Aubry. 1991. ''Effects of rainfall, vegetation and microtopography on infiltration and runoff'', *Water Resources Research*, Vol. 27, pp. 2271–2285.

Evans, R. and D. W. Kirkland. 1988. ''Evaporite environments as a source of petroleum'', in B. C. Schreiber (ed.) *Evaporites and Hydrocarbons*. New York: Columbia University Press, pp. 256–299.

Flügel, E. 1978. *Mikrofazielle Untersuchungen von Kalken*. Berlin: Springer Verlag.

Folk, R. L. and L. S. Landes. 1975. ''Mg/Ca ratio and salinity: Two controls over crystallization of dolomite'', *Bulletin of the American Association of Petroleum Geologists*, Vol. 59, No. 1, pp. 60–68.

Gregor, M., B. Schütt, and G. Förch. 2004. ''Land-use/land-cover changes in the Lake Abaya-Chamo basin, south Ethiopia, since 1981 – A remote sensing based analysis'', in B. Wenclawiak and S. Wilnewski (eds) *Sedimentary Studies in Tropics and Subtropics*. Weiterbildung in Siegen No. 14, pp. 3–15.

Heim, D. 1990. *Tone und Tonminerale*. Stuttgart: Enke Verlag.

Horton, R. E. 1945. ''Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology'', *Geological Society of America Bulletin*, Vol. 56, pp. 275–370.

Krauskopf, K. B. 1956. ''Dissolution and precipitation of silica at low temperatures'', *Geochimica et Cosmochimica Acta*, Vol. 10, pp. 1–26.

Lerman, A. 1979. *Geochemical Processes – Water and Sediment Environments*. New York: John Wiley & Sons.

Livingstone, D. 1984. ''The observation of algal remains in recent lake sediments'', in E. Y. Haworth and J. W. G. Lund (eds) *Lake Sediments and Environmental History*. Leicester: Leicester University Press, pp. 191–203.

Macedo, J. and R. B. Bryant. 1989. ''Preferential microbial reduction of hematite over goethite in a Brazilian Oxisol'', *Soil Science Society of America Journal*, Vol. 53, pp. 1114–1118.

Meyers, P. A. and R. Ishiwatari. 1993. ''The early diagenesis of organic matter in lacustrine sediments'', in M. H. Engel and S. A. Macko (eds) *Organic Geochemistry – Principles and Applications*. New York: Plenum Press, pp. 185–209.

Rheinheimer, G. 1974. *Aquatic Microbiology*. New York: John Wiley & Sons.

Richter, G. 1976. ''Was ist Bodenerosion?'', *Wege der Forschung*, Vol. 430, pp. 1–20.

Rohdenburg, H. and U. Sabelberg. 1973. ''Quartäre Klimazyklen im westlichen Mediterrangebiet und ihre Auswirkungen auf die Relief- und Bodenentwicklung'', *Catena*, Vol. 1, pp. 71–180.

Rogers, R. D. and S. A. Schumm. 1991. ''The effect of sparse vegetation cover on erosion and sediment yield'', *Journal of Hydrology*, Vol. 123, pp. 19–24.

Schütt, B. 1998. ''Chemical and mineralogical characters of lacustrine sediments as paleonvironmental indicators – An example from the Laguna Jabonera, central Ebro basin'', *Terra Nostra*, Vol. 98, No. 6, pp. 115–120.

Schwertmann, U. and R. M. Taylor. 1989. ''Iron oxides'', in J. B. Dixon and S. B. Weed (eds) *Minerals in Soil Environments*, SSSA Book Series 1. Madison, WI: SSSA.

Seleshi Bekele. 2001. *Investigation of Water Resources Aimed at Multi-objective Development with Respect to Limited Data Situation: The Case of Abaya-Chamo Basin, Ethiopia*, Wasserbauliche Mitteilungen No. 19. Dresden: Institut für Wasserbau und Technische Hydromechanik.

Street-Perrott, F. A. 1980. ''The relative importance of climate and hydrogeological factors in influencing lake level fluctuations'', *Palaeoecology of Africa*, Vol. 12, pp. 137–158.

Street-Perrott, F. A. and S. P. Harrison. 1985. ''Lake levels and climate reconstructions'', in A. D. Hecht (ed.) *Palaeoclimate Analysis and Modelling*. New York: John Wiley & Sons, pp. 291–340.

Ulrich, B. 1981. ''Ökologische Gruppierung von Böden nach ihrem chemischen Bodenzustand'', *Zeitschrift für Pflanzenernährung und Bodenkunde*, Vol. 144, pp. 289–305.

Vallentyne, J. R. 1962. ''Solubility and the decomposition of organic matter in nature'', *Archiv für Hydrobiologie*, Vol. 58, pp. 423–434.

8

Land use changes and hydrological responses in the Lake Nakuru basin

S. K. Murimi and Haushila Prasad

Introduction

Since 1944–1945, agricultural colonization of former government forests in the endorheic Lake Nakura basin has affected the balance of water resources in this part of Kenya. This chapter seeks evidence of the impacts through the analysis of rainfall, evaporation, river flow, and lake-level datasets. There has been no recent shift in rainfall patterns. However, there has been a consistent decline in river flow magnitudes and an increase in the frequency of low-flow events across all recurrence intervals for the period 1958–1996. There has also been a decline in lake levels, although the trend line is not statistically significant. The cause could be increased surface and subsurface abstractions for domestic and irrigation purposes.

Shallow tropical lakes are inherently unstable, relying upon unpredictable amounts of seasonal rains and faced with high evaporation rates. In addition, human life may directly threaten the health of the lakes and their surrounding wetlands through elevated concentrations of silt, pesticide and fertilizer residues in runoff, and surface and subsurface abstractions within drainage basins. Despite this unpredictability, the lakes and their associated wetlands are valuable natural resources (Podolsky and Conkling, 1991). Concern has been expressed that the shallow tropical lakes in Africa, especially those in the eastern Rift Valley, appear to be drying up and are also becoming potentially toxic to both animals and plant life. Lake Nakuru, one of the shallow lakes in the central Rift Valley of Kenya, is an endorheic (closed) lake system lacking a signifi-

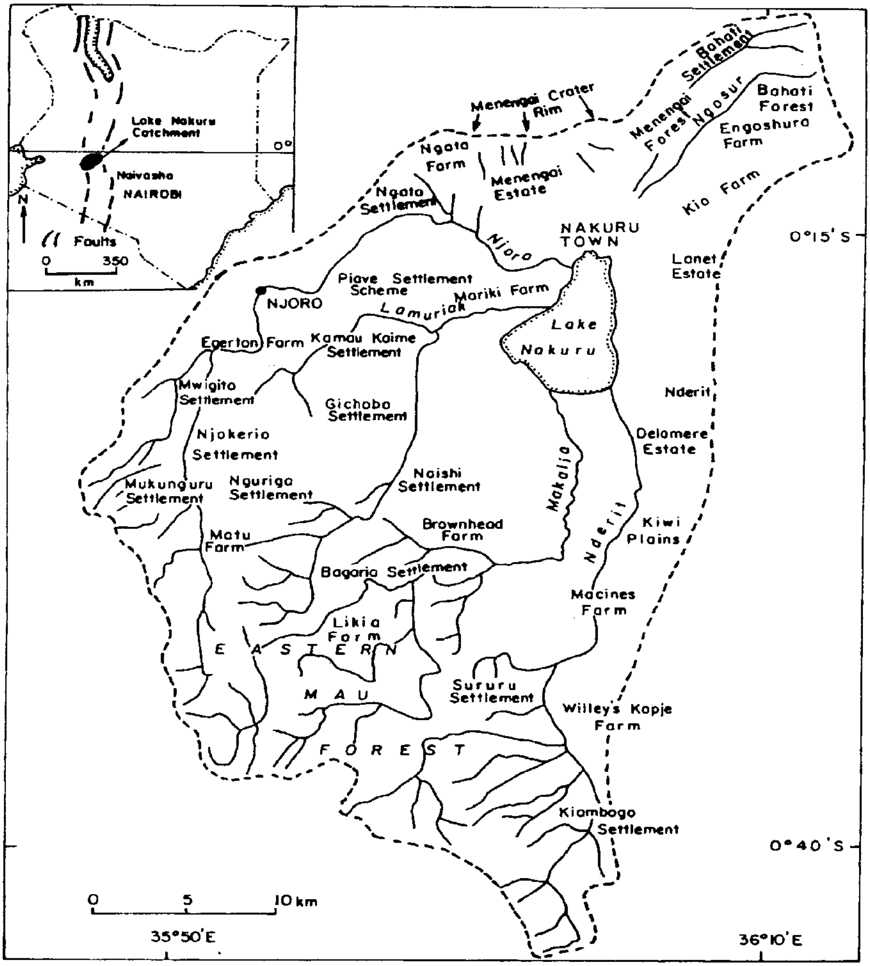

Figure 8.1 Location map

cant outlet. Its drainage basin lies between latitudes 0° 15′ and 0° 50′ S and longitudes 36° 10′ and 36° 50′ E, and covers in the central Rift Valley of Kenya (Figure 8.1).

The basin covers a surface area of 1,292 km^2, ranging in elevation from 1,728 metres at the modern lake shore to about 3,000 metres on the Mau hills. The lake is a shrunken remnant of a much bigger lake that used to occupy the Nakuru-Elmenteita basin in the Holocene. This single, large, deep, freshwater lake was in existence about 9,500 years BP (Richardson and Dussinger, 1986). Its lake level appears to have fallen during the hypsithermal period in East Africa, which is about the same time as the onset of the arid phase in parts of the Sahara. About 5,000 years BP Lake Nakuru-Elmenteita split to form Lakes Nakuru and Elmenteita, which were confined to their own basins (Washbourn, 1967). These two lakes reached their lowest levels at about 3,000 years BP. Since then there have been minor fluctuations of the small lakes that now occupy the lowest part of the basin. At present the lakes are shallow bodies of highly alkaline water (sodium carbonate salts) whose depth and area have varied strikingly this century. This, according to Murimi (1994), could be attributed to either climatic and/or geologic factors as well as changes in land use within the drainage basin.

The Lake Nakuru drainage basin contains agricultural land, non-agricultural land (forest, wetland, grassland, and bushland), and built-up (urban) land. The land cultivated and its total output have increased since farmers were allowed to colonize former reserved forests from 1994 to 1995 (Republic of Kenya, 1997). According to the Nakuru District Development Plan Kenya (Republic of Kenya, 2000), these former government forests have been cleared to settle about 30,000 families in areas such as Teret, Sururu, and Likia in Njoro. This area is a critical water catchment zone for Lake Nakuru. An understanding of the ways in which water passes through a drainage system is fundamental to many aspects of lake basin management. The prediction of peak flows, total flows at different stages, and source areas is necessary for designing control measures and developing and evaluating scenarios that can counter declining flows into rivers and the lake.

Materials and methods

This research project used the following data.

Rainfall

Data from six rainfall gauging stations around and within the catchment of Lake Nakuru were analysed. Each station was selected with regard to its position within or around the drainage basin and also its data record length. Areal rainfall monthly totals over the drainage basin of Lake Nakuru were calculated using the Thiesson polygon method. This method involves joining of adjacent stations by straight lines and then erecting perpendicular bisectors on each of the lines, thereby forming a series of polygons each containing one and only one rainfall station.

Evaporation

Nakuru meteorological station was treated as the reference for the lake's evaporation amounts. The station is at an altitude of 1,873 metres, while the altitude of Lake Nakuru at the modern lake shore is about 1,728 metres. Evaporation is largely controlled by solar radiation and altitude. If altitude is constant then evaporation does not vary much (Penman, 1948). Monthly evaporation amounts for the period 1972–1996 were calculated for the study.

Stream discharge

Stream discharge data for three river gauging stations (RGSs), 2FC5, 2FC11 (both upstream), and 2FC9 (downstream), along the River Njoro were obtained from the hydrology section of the Ministry of Water Resources, Nairobi. Station 2FC11 is on a fingertip tributary (the Little Shuru) of the River Njoro, while station 2FC5 is after the confluence. The data comprised maximum and minimum monthly flows in cumecs (m^3s^{-1}), for the period 1958–1996.

Lake levels

Lake-level data for the period 1958–1996 were also obtained from the hydrology section of the Ministry of Water Resources. Lake Nakuru has one lake-level measuring station, located at the northern side of the lake. The lake-level data consisted of mean monthly levels in metres.

Data treatment and analysis

The frequency and trends of low-flow characteristics in rivers, both cyclic and non-cyclic, were examined. Graphs plotted on a monthly basis to illuminate interrelationships between variables were also utilized.

Calculation of trends

Data on rainfall and lake levels were plotted against time for all the years considered and the overall trend for each was calculated by use of cyclic methods. This was achieved by employing five-year running means to annual mean values. This method reduces the influence of short-term fluctuations, smooths data, and also visually illuminates any existing trends. To generate five-year running means, the first five annual means are averaged and the value obtained is entered against the third year.

Then, starting with the second annual mean, the next five years' values are averaged and the value obtained is plotted against the fourth year. This stepwise averaging is continued until all the data are used.

However, these plots of average rainfall amounts and their five-year running means for the watershed reveal a fairly stable cyclic pattern. This suggests that, historically, rains over the Lake Nakuru drainage basin have not differed much in regime between the past and present, and that through the years under consideration the drought and wetness intensities have followed the same pattern. If the trend in lake levels is real, this means that it is probably not due to changes in rainfall.

Regression analysis

Simple linear regression analysis was used to predict annual lake levels (functional relationship) over time. This was done by first plotting a scattergram and then plotting the regression line (trend line) through the scattergram. The slope indicates the change in lake levels over time. The significance of the regression line was determined by the use of t-distribution to establish whether or not the form of the trend occurs just by chance (Figure 8.2). The results obtained from the regression line for lake levels (Figure 8.2) indicates the probability of the trend being significant as $p \geq 0.2$.

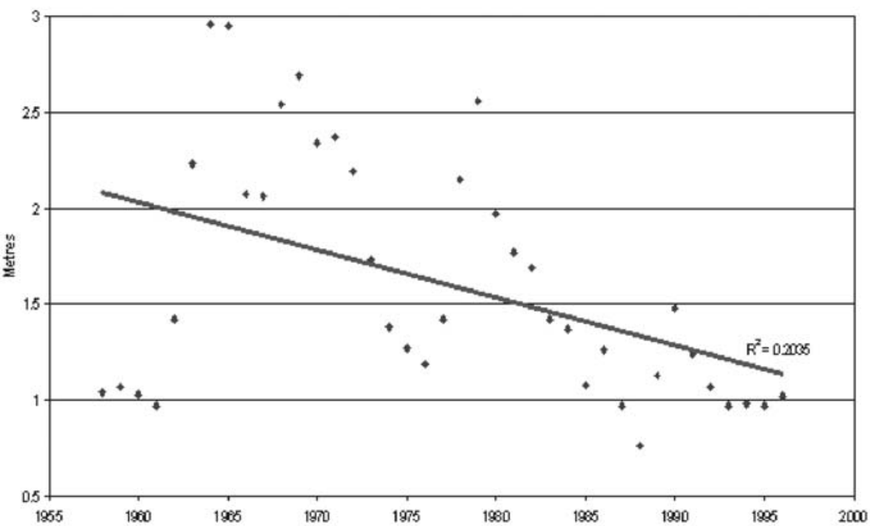

Figure 8.2 Regression line (trend) of mean annual lake levels of Lake Nakuru

Monthly evaporation data from Nakuru meteorological station showed a moderate variability and a similar, if less obvious, decline. In general, the standard deviation of monthly evaporation is about 10.7–20.6 per cent of the mean. Plots of total monthly evaporation indicate a decrease in most recent times. A decrease in evaporation should cause an increase in lake levels, hence an inverse relationship, but this is not the case. However, evaporation depends on both water availability and meteorological factors. This means that the observed decrease could be due to decreasing surface water and soil moisture in the unsaturated zone. This assertion needs to be confirmed by thorough studies that involve reducing plotted evaporation figures by the pan coefficient factor to calculate approximate lake evaporation.

Analysis of seasonality patterns

Monthly mean values for stream discharge at three gauging stations along the River Njoro were plotted to show any distinctive seasonality and regime patterns, respectively, during the year. The plots were also used to reveal whether the river regime exhibits a seasonal pattern and illuminate any interrelationships between discharges at various points along the River Njoro.

Considering the wettest and driest monthly conditions (that is, maximum and minimum monthly flows respectively), key differences showed up. Maximum monthly flows (wet conditions) show a consistent increase in discharge from the fingertip tributary down to the depositional lowlands, and by inference into the lake. Surface runoff and wastewater discharge into the river by the Njoro canning factory, Egerton University, Njoro town, KARI, and other institutions along the river could probably be contributing factors to the higher discharge downstream than upstream in the rainy (wet) part of a month. Graphs of minimum monthly flows, representing drought conditions, show that the downstream section of the river has lower discharge than the headwater zone. In some months, especially during the dry season (January and October), the tributary River Shuru (at RGS 2FC6) has more water than the main River Njoro (RGS 2FC11 and 2FC9). Then, for almost all months in the year, the upstream section (RGS 2FC11) has more water than RGS 2FC9, which is lower down the course of the river. This suggests that during drought conditions there might be other factors coming in as the River Njoro approaches the lake. That flows past certain points along the river are decreasing during dry conditions in view of an apparently unchanging rainfall regime suggests water losses in between the source(s) and the mouth of river.

Analysis of extreme flow values

The frequency and probability of extreme low-flow events at discharge measuring stations along the River Njoro were examined. Frequency of low flows is an important tool for describing hydrological data and for drought prediction. This method gives the number of times, within a certain period of time, that a specified discharge was equalled or exceeded.

Minimum monthly flow data for the period 1958–1996 were rearranged into their order of magnitude to show the number of times that each discharge was equalled or exceeded. Cumulative frequencies for discharge values were then used to construct a flow duration curve. Gumbel analysis of extreme values was also utilized to compare low-flow characteristics at the discharge gauge station next to the lake. To establish the time relationship between low flows, minimum monthly flows were selected from five blocks of years. For each block, the flows were ranked and then transformed into natural logarithms so as to linearize the abscissa of the Gumbel probability paper. This allows a Gumbel distribution to plot as a straight line on a Gumbel EVIII paper. To do this, minimum monthly discharges were ranked in descending order and plotted against the corresponding recurrence interval using Weibull's plotting position, $(m - 0.31)(n + 0.38)$, where m is the rank of a given flow and n is the total number of observations.

From the plots, the flows for a given return period were tabulated in order to compare the low-flow characteristics over the different blocks of years. The extreme value probability analysis of low flows indicates that flows for a given return period decrease for successive blocks of years. Table 8.1 indicates a consistent decline in flow magnitudes across all recurrence intervals for the period 1958–1996, and decreasing inflow to the lake. The flow duration curve also shows that in most recent years the proportion of time for which given flows were equalled or exceeded continues to decrease.

Table 8.1 Flow magnitude for given return periods at RGS 2FC9 along River Njoro

Return period months	1958–1965	1966–1973	1974–1981	1982–1989	1990–1996
1.15	0.05	0.03	0.02	0.01	0.00
1.20	0.23	0.17	0.11	0.08	0.05
2.39	0.42	0.38	0.28	0.24	0.17
3.48	0.49	0.39	0.34	0.28	0.25

Discussion

The study examines how climatic elements (of rainfall and evaporation) relate to the water levels of Lake Nakuru and the rivers draining into it. It also evaluates the flow-rate characteristics of the River Njoro, and this may be used to give an indication of natural and human influences along the river. Analysis of annual lake levels shows a negative cyclic pattern, indicating a decrease of water depth in Lake Nakuru. This trend is not conventionally statistically significant, but the $p > 0.2$ level suggests that there is a 20 per cent probability. This means that the study is 80 per cent sure that the regression line predicts the real trend of water levels in the lake. This may be expected to continue in the future. Currently, it may be seen that some gauge height measuring equipment which was once used to record lake levels is left standing a distance from the water level of the lake. There is some suggestion that the amount of lake evaporation has also declined, but this may be the result of the decline in lake levels and drying of the landscape.

The consistent decline in flow magnitudes across all recurrence intervals for the period 1958–1996 in the River Njoro and its tributaries, which is smallest in the headwaters, is possibly caused by surface and subsurface abstractions for domestic and irrigation purposes. Surface abstractions through diverting, damming, and pumping of water directly from the river were found to have taken place along the River Njoro and its tributaries. Similar observations were also noted in Lake Nakuru basin, where diverting water for farming purposes had in 1965–1966 reduced the amount of water in Ngosur stream on the Bahati plains. Subsurface abstractions (from boreholes) could lead to the lowering of the groundwater table, hence reducing the amount of groundwater emerging along river channels. Unfortunately, the amounts of water abstracted from both the surface and groundwater cannot be exactly known, since for surface abstractions the permits issued by the Ministry of Water Resources only state the quantities allowed to be abstracted during low and high flows. In the case of subsurface abstractions, the ratios of pumping from boreholes have not been strictly enforced and so cheating in the quantities pumped is possible.

Falling water levels in rivers and the lake could also be linked to geological faults in the drainage basin. The Lake Nakuru basin lies in a seismically active zone where the Rift Valley makes its most dramatic appearance. Here the valley makes a great slash in the earth's surface, 525 m deep and 32 km wide. According to Nyamweru (1980), the current plate tectonic theories indicate that the Rift Valley seems to be opening up slowly, probably at a rate of up to 0.02 cm a year. It is expected that this movement causes cracks in the drainage basin. These outlets will drain away some of the water before it flows into the lake, especially if they emerge on the channel bed of the streams. According to the Nakuru District Development Plan Kenya (Republic of Kenya, 1997), the Rivers Njoro, Larmudiac, Makalia, and Nderit, which drain down the Mau escarpment, lose much of their water to porous and fissured zones in this part of the basin. However, in this case the increase of the human activity in the area is a more likely cause of the observed patterns.

Conclusion

Long-term trends in the climatic elements of rainfall and evaporation amounts show different characteristics. Plots of five-year moving averages of rainfall revealed a kind of cyclic variation in the averages but no trend component. This suggests that the rainfall regime has not changed significantly. By contrast, lake levels seem to be in decline, and the same is true of monthly evaporation amounts.

A consideration of plots of areal monthly rainfall totals and discharge at different sections along the River Njoro confirms that streamflow is sustained by the rains falling within the watershed of Lake Nakuru. The volume of water in rivers is expected to increase in the downstream direction, a situation the current study found not to be the case for the River Njoro during dry conditions. The trends of stream discharge near the lake (RGS 2FC9) reveal decreasing inflows into the lake over different blocks of years. A consideration of the flow duration curve indicated that in most recent times the proportion of time for which given low flows were equalled or exceeded continues to decrease. This implies a drying up of rivers draining into the lake, especially in the downstream direction, and this trend increases towards the present day.

The fact that flows past certain points along the River Njoro are decreasing despite an apparently unchanging rainfall regime suggests water losses in between the source and the destination. Possible explanations for the decrease during dry conditions include damming, surface abstractions for domestic and irrigation purposes, and pumping through boreholes. All this results in less net water inflow that consequently decreases the volume of water in Lake Nakuru.

REFERENCES

Murimi, S. K. 1994. "Falling water levels in saline lakes of central Rift Valley in recent times", *Journal of Salt Lake Research*, Vol. 3. pp. 65–74.

Nyamweru, C. 1980. *Rifts and Volcanoes*. Nairobi: Thomas Nelson.

Penman, H. L. 1948. ‘‘Natural evaporation from open water, bare soil and grass’’, *Proceedings of the Royal Society of London*, Series 4A – 4193. London: Royal Society, pp. 120–146.

Podolsky, R. and P. Conkling. 1991. ‘‘Satellite search aids wetlands visualization’’, *GIS World*, Vol. 4, pp. 80–85.

Republic of Kenya. 1997. *Nakuru District Development Plan*. Nairobi: Government Press.

Republic of Kenya. 2000. *Nakuru District Development Plan*. Nairobi: Government Press.

Richardson, J. L. and R. A. Dussinger. 1986. ‘‘Palaeolimnology and mid-elevation lakes in the Kenyan Rift Valley’’, *Hydrobiologia*, Vol. 143, pp. 167–174.

Washbourn, C. K. 1967. ‘‘Late Quaternary lakes in the Nakuru-Elmenteita basin’’, unpublished PhD thesis, University of Cambridge.

9

Hazard risk assessment in Mount Kenya headwaters

Alfred Opere

Introduction

Water is life! It is essential for all aspects of our livelihood, from basic drinking water to food production and health, from energy production to industrial development, from sustainable management of natural resources to conservation of the environment. Water also has religious and cultural values. Unfortunately, water is becoming scarce in many areas and regions of the planet. The latest data from the World Water Council's report on sustaining water (1996) show clearly how alarming the situation is:

> In 1950, only 12 countries with 20 million people faced water shortages; by 1990 it was 26 countries with 300 million people; by 2050 it is projected to be as many as 65 countries with 7 billion people, or about 60 per cent of the world's population, mainly in the developing countries.

The report calls for immediate and effective action in order to maintain fresh water availability in the coming century. As documented in the recently published report on fresh water management (Liniger *et al.*, 1998), mountains play a crucial role in the supply of fresh water to humankind, in both mountains and lowlands.

All the major rivers of the world have their headwaters in highlands, and more than half of humanity relies on the fresh water that accumulates in mountain areas. Although they constitute a relatively small proportion of river basins, most of the river flow downstream originates in mountains, the proportion depending on the season. These "water-towers" are crucial to the welfare of humankind. As demand grows, the potential for conflict over the use of mountain water increases. Careful management of the sources of water as well as of the resources themselves must therefore become a global priority in a world moving towards a water crisis in the next century.

The need to focus on mountains

There are many reasons why we need to focus on mountains, among which the following can be highlighted as the most important.

High precipitation levels

Mountains form a barrier to incoming air masses. Forced to rise, the air cools, triggering precipitation. In semi-arid and arid regions, only highlands have sufficient precipitation to generate runoff and groundwater recharge.

Storage and distribution of water to the lowlands

Waters captured at high altitudes flow under gravity via the stream network or groundwater aquifers to the lowlands, where the demand from population centres, agriculture, and industry is high. For example, the 1.4 million people of La Paz and El Alto (Bolivia) depend mostly on water supplies from surrounding glaciers lying above 4,900 m above sea level, and 75 per cent of the electric power for these cities is generated by the hydropower plants on the eastern escarpment of the Andes.

In humid areas throughout the world, the proportion of water generated in the mountains can comprise as much as 60 per cent of the total fresh water available in the watershed, while in semi-arid and arid areas this proportion is generally over 90 per cent.

The life-sustaining role of water

Clean and reliable water supply is fundamental to human existence and health. Since 1940, global fresh water abstractions from all sources (i.e. extraction for use of surface water or groundwater) have more than quadrupled (Figure 9.1). Seventy per cent of the water is used for irrigation. The dependency of world food production on mountain waters is evident, particularly in the arid and semi-arid climates of the tropics and subtropics where most of the developing countries and more than half of

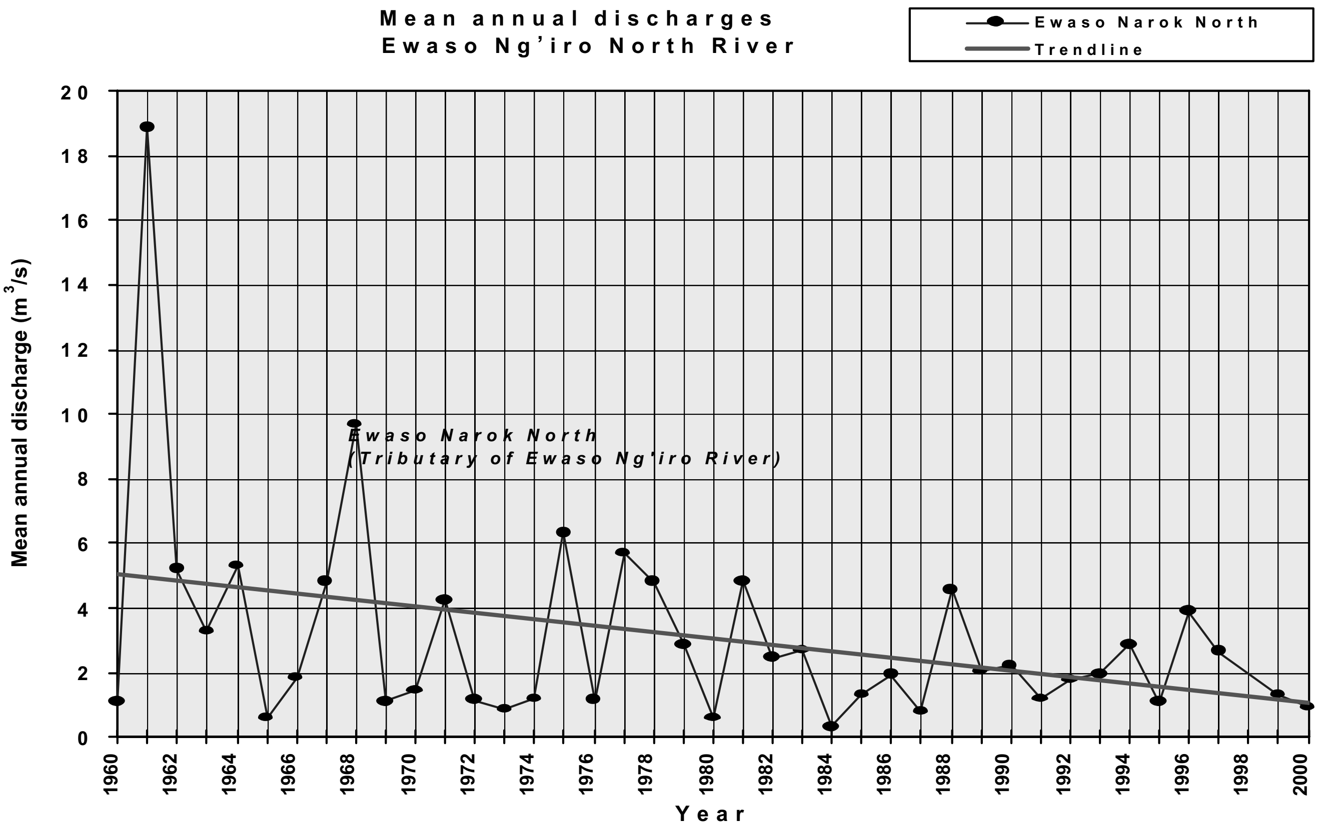

Figure 9.1 Declining flows of Ewaso Ng'iro North River

the world's population are located. Furthermore, water stored in mountain lakes and reservoirs has additional economic value as a potential source of hydroelectric power. Mountain fresh water also sustains many natural habitats, in both highlands and lowlands, thus contributing to the conservation of biodiversity.

Fragile ecosystems

Mountains are highly fragile ecosystems. High rainfall, steep slopes, and erodible soils can induce severe surface runoff, soil erosion, and landslides. Eroded sediments are major pollutants of surface waters. Land use, development of infrastructure, mining, and tourist activities in mountain areas may significantly affect the quantity and quality of river water and groundwater.

Conflicts over water

Worldwide, 214 river basins, host to 40 per cent of the world's population and covering more than 50 per cent of the earth's land surface, are shared by two or more countries. The distribution of water from mountain areas was the cause of 14 international conflicts noted in 1995. For example, the Arab–Israeli conflict, although primarily a security and territorial dispute, also involves the supplies of fresh water from the Anti-Lebanon mountains, Mount Hermon, the Golan Heights, and the hills of the West Bank. Disputes over water also arise on a smaller scale between highlands and lowlands within national borders – as, for example, around Mount Kenya.

"Sacred" mountain water

Throughout the world people have always looked to mountains as the source of water, life, fertility, and general well-being. Mountains have been, and in some places still are, worshipped as the home of deities and as the source of clouds and rain that feed springs, rivers, and lakes on which societies depend for their very existence.

Mountains as moderators of local and regional climate

Mountains influence the local and probably global climates. In the global and regional circulation of air masses, mountains intercept air masses and force them to rise. As the air rises, it cools and water droplets are formed, thereby triggering precipitation. Part of this precipitation falls in the mountain areas and the remainder in the surrounding lowlands. Generally, elevation controls the quantity of rainfall at the regional scale, whereas topography strongly influences rainfall distribution at the local scale. Mountain vegetation also transpires a huge amount of water, which contributes to the return of the water to the atmosphere. Forests have important functions in relation to climate. Cloud forests in mountain areas capture water from mists and moving clouds (Hamilton, 1996). Vast forest cover helps to regulate rainfall, relative humidity, temperature, and wind regimes. Due to the altitudinal gradient, the mountains moderate the diurnal range of air temperatures and maintain atmospheric humidity levels. Due to the low temperatures and high relative humidity, mountain areas have low evaporation rates. The combination of low evaporation and higher rainfall makes highlands and mountains areas the main areas for runoff generation and groundwater recharge, particularly in the African continent, which consists of extensive lowlands with scattered highlands and mountains.

Since most mountain areas have dense, vigorously growing vegetation, mountain vegetation constitutes an enormous carbon reservoir which absorbs carbon dioxide, thereby reducing the risk of global warming. When the vegetation, particularly the trees, is burnt or cut down, the carbon stored up over many years is released into the atmosphere, thereby increasing the level of carbon concentration in it and thus aggravating the greenhouse effect. Hence, the dense mountain and highland vegetation absorbs atmospheric carbon and replenishes the oxygen we breathe.

The water balance in mountain regions is more favourable than in the surrounding lowlands. This is attributed to the high rainfall and lower evaporation rates. Analysis of rainfall data for 808 rainfall stations in Africa shows that in general rainfall increases with elevation and evaporation rate decreases with increasing altitude: Mountain Agenda (1999) reported that rainfall thus generally increases with altitude (from 5 mm/100 m to 750 mm/100 m elevation, depending on the climatic zone), reaching maximum values between 1,500 and 4,000 m altitude. Closer analysis of the rainfall-elevation relationship of the western side (rain shadow) of Mount Kenya shows that rainfall increases with elevation up to an elevation of 3,300 m above sea level, from where it decreases as elevation increases.

Impact of mountain resource management on fresh water supply

The Mount Kenya experience – Direct and indirect human impact

Rivers originating from the glaciers of Mount Kenya flow through the montane and high-elevation moorland to the forest belt, where rainfall is highest and rivers and groundwater aquifers are recharged. Ninety per cent of the dry season flow of the Ewaso Ng'iro River collects in the alpine, moorland, and montane forest belts (above 2,400 m) on Mount Kenya. On the lower mountain slopes and in the piedmont, both the population and the area of cultivation have more than tripled over the last 20 years and river water abstractions for irrigation have dramatically increased. Currently, 60 per cent of the people in the Ewaso Ng'iro basin live in this area and the remainder live downstream on the semi-arid plains, where they depend for their livelihood on water generated upstream.

Decreasing dry season river flow is a serious problem; since the 1960s, the average dry season flow of the Ewaso Ng'iro River has been reduced in the lowlands to one-eighth of its previous level. Since the 1980s, the once perennial river has had prolonged periods with no flow. Consequently, the unique wildlife ecosystems of the Samburu and Buffalo Springs game reserves in the lowlands suffer during the drought period and this has had a negative impact on tourism, the primary source of foreign exchange in the region. Nomadic pastoralists and their livestock, and the wildlife in the lowlands, are drastically affected and are forced to move upstream in the search for water and grazing land. As a result, conflicts with farmers are increasing. A clear example of diminishing flows of the Ewaso Ng'iro North River is shown in Figure 9.1.

Two main factors are affecting river flow in the lowlands

Increasing water abstractions

A growing population and immigration into the area surrounding Mount Kenya increase the water needs for drinking, for industrial and urban use, and, most important, for irrigation. In addition, the control and management of abstractions are inadequate. Currently, 10 times more water is taken out than regulations, if properly supervised, should allow. Monitoring of abstractions, improved procedures for allocation, and better management and control are urgently needed.

Land-use change and intensification

Changes in land use have also had an impact on river flow and water quality. Removal of vegetation cover and intensified land use on the northern slopes of Mount Kenya have led to increased surface runoff during heavy storms, causing erosion and pollution of the surface water. Flash floods, previously unknown, have been recorded in recent years, flooding old farmhouses and tourist lodges. Investigations are still being undertaken to quantify the impact of human activities and land-use change on runoff and floods, and on river flow during the dry season.

Soil moisture measurements under different land uses show the amount of water lost through evapotranspiration. A comparison of natural forests with plantations and cropland on Mount Kenya showed that soil under cypress plantation was the driest, as the water was used up much faster than under natural forest. Rainfall was not sufficient to recharge the groundwater. Under natural forest, the soils were moister and there were periods of groundwater recharge. It is only natural that a fast-growing tree will use more water than a slow-growing one in absolute terms (but not necessarily so in terms of consumption per cubic metre of wood produced).

Under crops such as potatoes the soils had a higher water content and groundwater recharge was the highest. Although surface runoff occurred during heavy storms, cropland still provided the greatest contribution to groundwater and river flow.

Impact of mountain land use on fresh water resources and the role of forests

Case studies indicate that there are both direct and indirect impacts of mountain resource use.

There are two main direct impacts: water use from rivers and aquifers, such as surface abstractions and the pumping of groundwater, affects the quantity of water; and point-source pollution, such as wastewater discharge into rivers, affects water quality.

Clear-cutting of forests and overgrazing were thought to be the main causes of severe floods resulting in extensive damage.

The influence of the forest in reducing peak runoff ceases as soon as the soil becomes saturated. Any additional rainfall will run off immediately and quickly reach river channels, thus causing floods. Since these impacts can be identified, if there is a need and political will regulations can be introduced to control both water use and waste discharge (including water treatments and the use of certain chemicals).

The indirect impacts are land use that changes the water cycle and the quantity of water (e.g. river flow); and non-point-source pollution (also called land-based pollution), which influences the water quality. In many parts of the world this is the major source of river and groundwater pollution.

The indirect impacts are much more difficult to identify and quantify than the direct impacts because of the complicated interactions of land, soil, and vegetation, and thus they are more difficult to control.

What is the effect of land use on the availability of fresh water?

The key to assessing the impact of land use in the mountains on water resources is an understanding of how land-use changes, and particularly intensification, affect the water cycle. Rodda (1994) clearly expresses the challenge:

> From the hydrological point of view, mountain regions present a paradox. Although they provide the bulk of the world's water resources, knowledge of these resources is generally much less extensive, reliable and precise than for other physiographic regions.

As Klemes (1988) says, mountain regions represent, in practical terms, "the blackest of black boxes in the hydrological cycle".

If rainfall at any one time is greater than the infiltration rate of the soil (its capacity to absorb the water), surface runoff occurs. Accelerated runoff increases the risk of soil erosion, which reduces soil fertility and the capacity of the soil to store water. This may lead to reduced vegetation cover and productivity, forcing people to intensify land use. As a result, the vegetation is further degraded and productivity curtailed. The water cycle is changed and a vicious cycle of degradation is initiated (Liniger, 1995). As simple as this principle is, it is difficult to determine under which type of land use, under which soil type, and under what climatic conditions the cycle of degradation is initiated, and at what point the capacity to recover is lost for future generations.

Natural vegetation is generally characterized by high rates of infiltration compared with other types of land cover with a similar soil base. Because under natural conditions there are usually several storeys of vegetation, the top layers of the soils are well protected and well structured; any change from the natural growth to forest use, plantations, grazing land, and crop production may reduce infiltration and the storage capacity of the soil.

The change from natural forest cover to other types of land cover and land use has often been associated with degradation of natural resources. Observations and research findings show that in the first years following land-use change, when the vegetation cover is removed and the topsoil disturbed, high rates of runoff and soil erosion occur. However, depending on what the new land use is, after the early years of transition the negative impacts may be reduced as improved management practices are established and good vegetative cover is restored (Hamilton, 1987). Adequate soil cover and efficient management and conservation practices are important for sustainable use of resources. In mountains all over the world agricultural systems have been developed that do not destroy natural resources and that have locally well-adapted and sustainable systems of water and land use.

Changes in land use and vegetation affect not only runoff but also evapotranspiration. When cropland, grazing land, and forests are compared, cropland is found to have the lowest rate of evapotranspiration and forests the highest. Increased evapotranspiration reduces the groundwater recharge and the contribution to river flow. However, great differences occur according to the plant species and the rate of production.

Another difficulty in assessing the impact of land use on fresh water resources is the problem of scale (Hamilton, 1987). Whereas impacts at the local scale can be identified, the human impact in large basins is difficult to identify and appears to become insignificant.

What is the effect of land use on the quality of fresh water?

Any intensification of land use from natural forests to plantation or agriculture increases the probability of reduced water quality. Even if the water cycle is unchanged, use of fertilizers, insecticides, herbicides, or other substances may pollute water resources downstream. Siltation is also a problem where erosion rates increase as a result of removal of vegetative cover. As runoff increases, non-point-source pollution is likely to become a serious threat to water quality. Whereas in many cases point-source pollution has been reduced in recent years, non-point-source pollution has increased and is a much greater threat.

Further clarification of the role of mountain forests is needed

The role of providing and protecting water resources has been attributed to forests for generations. Folk tales and myths throughout the world illustrate that natural forests provide clear and pure water (Küchli, 1997). However, in only a few cases has this been properly documented and compared with other land uses (such as plantation forestry, grazing, or crop cultivation) in relation to river flows, groundwater recharge, and water quality. Whereas the impact of intensified land use on water quality is likely to be negative, there is not sufficient evidence to quantify this. Furthermore, the effects on the water cycle of water availability, erosion, and soil productivity still remain unclear in many cases. Mountain forests generally provide favourable conditions for storage of excessive rainfall, whereas runoff may be higher in other types of land cover and land use such as agriculture, where soils may be compacted through cultivation or overgrazing, which also reduces vegetative cover.

Although forest soils store water, evapotranspiration is also higher in forests than under other types of vegetation (Hamilton, 1987). Therefore, forests may use more water and leave less for river and groundwater recharge than other land-use types. Unfortunately, there have been few investigations of forest productivity and the different rates of water use. Furthermore, the role of natural mountain forests in capturing additional precipitation from mist (cloud forests) is not well established.

Forests have been protected by the "myth", supported by some proven facts, of being "good" to humankind. It is timely now to clarify the multiple roles of mountain forests. These include supplying clean and sufficient water and forest products, maintaining biodiversity, and protecting against natural hazards such as avalanches, landslides, and rockfalls, as well as influencing climate.

Threats in Mount Kenya region

Land and water resources degradation

Studies in the Mount Kenya area have shown that soil resources degradation is taking place at different intensities in different locations. Soil erosion is the most extensive soil degradation problem in the upper Ewaso Ng'iro North basin. Reduced infiltration rate is another form of soil degradation taking place in the denuded rangelands as surface sealing and crusting takes place. In cultivated wetlands, soil degradation is taking place mainly in the forms of loss of organic matter and salt build-up (salinity and alkalinity).

Water resources degradation is taking place mainly in the form of changes in flow regimes and water pollution. Changes in flow regime are seen in increased flood flow peaks and reduced low flow. This is attributed to land-use and management changes that reduce infiltration and groundwater recharge.

Decline in water yield from the glaciers on Mount Kenya and drainage of swamps have aggravated the situation. The main form of water pollution is sediment load associated with the high rates of soil erosion. Pollution by agricultural chemicals and industrial and human waste is increasing in localized areas. Destruction of riverine vegetation and drainage of swamps are reducing the natural capacity for water quality amelioration.

Degradation of vegetation resources is taking place in the mountain areas mainly through deforestation and in communal grazing areas mainly through overgrazing. Overgrazing is mainly attributed to:

- reduced access to grazing resources through agricultural expansion, urbanization, gazetting land for conservation, and insecurity in the lower basin
- increasing livestock numbers
- increased sedentarization

- low productivity of grazing land
- conversion of swampland previously used as dry season grazing land to cropland
- additional grazing pressure imposed by wildlife.

Mountain Agenda (1999) reported that any land-use changes in the headwaters of the Nile basin are of paramount importance to downstream irrigation. For example, land degradation in the mountains of Ethiopia has increased significantly in recent years due to expansion of agriculture, overgrazing, and subsequent soil erosion. This threatens both the local land users, through a reduction in soil productivity, and those living downstream in the lowlands, through sedimentation, which has increased rapidly since the late 1960s.

Fresh water scarcity

The experiences of the upper Ewaso Ng'iro North basin are used to highlight the issue of fresh water scarcity. The analysis of Ewaso Ng'iro North River flow data collected at Archer's Post from 1960 shows a clear trend of decreasing dry season flow.

During the period 1960–2000 the maximum mean annual flow recorded was 82.36 m^3s^{-1} in 1961 and the minimum was 6.8 m^3s^{-1} in 1980, with a mean of 20.8 m^3s^{-1}. The 10-year running mean indicates that the flow has been decreasing from 1970. During the period between April 1998 and December 2000, the daily mean flow peaked at 354 m^3s^{-1} in May 1998 and dropped to zero in February 1999 (Gichuki *et al.*, 1998). Archer's Post experiences the lowest flows in February, and the mean for this month has dropped from 9 m^3s^{-1} in the 1960s to 4.59 m^3s^{-1} in the 1970s, 1.29 m^3s^{-1} in the 1980s, and 0.99 m^3s^{-1} in the 1990s (Liniger, 1995). This reduction in flow is attributed mainly to increasing water abstraction upstream and drought cycles, as there was no corresponding decline in rainfall amounts over the same period.

Fresh water scarcity has resulted in increasing competition for the scarce water resources and in some cases there have been conflicts. Water-related conflicts occur in the basin at different levels: among water project beneficiaries (project level); between different water user groups (upstream versus downstream level); and between water users and environmentalists/resource managements (use versus conservation). Project-level conflicts occur within a water project where the water project beneficiaries are the key stakeholders. Conflicts at this level arise from inequitable water allocation and delivery, financial mismanagement, disputes over the unfair distribution of maintenance work, failure to observe by-laws, etc. Upstream versus downstream conflicts occur between irrigation and non-irrigation water users, mainly over very low dry season river flows. Conflicts at this level arise from overabstraction of water by upstream water users, pollution of water, lack of cooperation between different user groups, disputes generated by jealousy related to growing wealth disparities, and conflicts between indigenous resource users and recent settlers. Use versus conservation conflicts occur between those benefiting from direct use of water and those benefiting from environmental functions (e.g. tour operators/hoteliers operating in the basin). Conflicts at this level arise from environmental degradation associated with the drying up of the lower reaches of the river, migration of wildlife to upper reaches in search of water and grazing resources, and associated loss of income.

The key actors in these conflicts fall into the categories of active or passive parties. They include environmentalists, small- and large-scale irrigators, nomadic pastoralist and commercial ranchers, downstream hoteliers and tour operators, and downstream communities (living below Archer's Post).

Conclusions

Mountains are of paramount importance in the supply of water for drinking and for food, energy, and industry. Fresh water from mountain areas also supports unique ecosystems and biodiversity in both highlands and lowlands. Mountain regions are under pressure from deforestation, agriculture, and tourism, and from increasing demands on their resources in the densely populated lowlands. In many regions mountains are marginal areas for human habitation, as steep slopes, poor soils, cool temperatures, and inaccessibility limit them. The surrounding lowlands are usually more favourable for settlement, agriculture, and industry, but remain dependent on the mountains for water resources.

Monitoring of natural resources and their use and assessment of the impact of land-use change in the highlands on the availability and quality of water in the lowlands are the first steps towards successful management. Whereas the effects of land-use change on surface runoff and erosion can be clearly quantified in test plots and small catchments, the effects on regional hydrology need further investigation (Liniger and Gichuki, 1994). This will lead to better understanding and determination of crucial limits or thresholds for land use and land-use intensification.

Integrated resource management encompassing both the mountains and the lowlands is needed at the local, national, and international levels, together with better cooperation between researchers, planners, decision-makers, and users at all levels. The impacts of future human activities upstream on the availability of resources downstream need to be assessed so that mutually beneficial policies can be introduced. Only integrated basin management can ensure efficient use, equitable distribution, and effective management and regulation of mountain water for the benefit of all humankind.

REFERENCES

Gichuki, F. N., H. P. Liniger, L. MacMillan, G. Schwilch, and G. Gikonyo. 1998. ''Scarce water: Exploring resource availability, use and improved management'', *Resources, Actors and Policies – Towards Sustainable Regional Development in the Highland-lowland System of Mount Kenya. Eastern and Southern Africa Journal*, Vol. 8, Special Issue, pp. 15–28.

Hamilton, L. S. 1987. ''What are the impacts of Himalayan deforestation on the Ganges-Brahmaputra lowlands and the delta? Assumptions and facts'', *Mountain Research and Development*, Vol. 7, p. 3.

Hamilton, L. S. 1996. ''The role of protected areas in sustainable mountain development'' (sections on ''Water production'', ''Riparian buffer zones'', and ''Cloud forests''), in Commission on National Parks and Protected Areas of IUCN – World Conservation Union.

Klemes, V. 1988. ''Foreword'', in L. Molnar (ed.) *Hydrology of Mountainous Areas*, IAHS Publication No. 90. Amsterdam: IAHS.

Küchli, C. 1997. *Forests of Hope, Stories of Regeneration*. London: Earthscan.

Liniger, H. P. 1995. ''Endangered water – A global overview of degradation, conflicts and strategies for improvement'', Development and Environmental Report No. 12, Centre for Development and Environment. Berne: Lang Druck.

Liniger, H. P. and F. N. Gichuki. 1994. ''Simulation models as management tools for sustainable use of natural resources from the top of Mount Kenya to the semi-arid lowlands'', Laikipia Mount Kenya Papers D-19. Nairobi: Nanyuki.

Liniger, H. P., R. Weingartner, M. Grosjean, C. Kull, L. MacMillan, B. Messerli, A. Bisaz, and U. Lutz. 1998. *Mountains of the World: Water Towers for the Twenty-first Century. A Contribution to Global Freshwater Management.* Berne: Mountain Agenda/Paul Haupt.

Mountain Agenda. 1999. *Mountains of the World: Water Towers for the 21st Century*. Berne: Mountain Agenda.

Rodda, J. C. 1994. ''Mountains – A hydrological paradox or paradise?'', *Beiträge zur Hydrologie der Schweiz*, Vol. 35, pp. 41–51.

World Water Council. 1996. *Mountains of the World: Water Towers for the 21st Century Part 1*, prepared for the Commission on Sustainable Development (CSD) project on Strategic Approaches to Freshwater Management. World Water Council.

10

An analysis of accessibility to rural domestic water supply: A case study of Kakamega district, Kenya

Chris A. Shisanya and Zachary A. Kwena

Introduction

The major objective of this study in rural Kenya was to establish the sources of domestic water supply and time/distance covered to water points. To achieve this objective, both documentary and field-based techniques were used to collect and analyse the required information. Interview schedules, key informant interviews, and focus group discussions were used to gather the data required for this study. The focus was mainly on sources of water, distance to water points, time spent collecting, amount of water used, trips made to water points, and nature of the route to water points. Descriptive statistics (frequencies, percentages, means, and cross-tabulations) as well as inferential statistics (chi-square, two-way ANOVA, and multiple regression) were used and information presented in tables, pie charts, and graphs. Out of the 300 respondents, 85 per cent and 77 per cent collected domestic water from springs during dry and rainy seasons, respectively. Over 74 per cent of the respondents got water from a roof catchment during the rainy season. Less than 10 per cent of the respondents used other sources of water during both dry and rainy seasons. Cross-tabulation between water sources and sub-locations revealed that some sources of water such as tap, stream/river, and well were sub-location specific. However, springs and roof catchments as sources of water were used across all sub-locations.

The water requirements per day per household differed greatly, ranging between one jerrycan (20 litres) and 36 jerrycans (720 litres) depending on the size of the household. On average, respondents use six jerrycans (120 litres) of water per day. Thus, based on average daily per-capita water requirements of 120 litres and an average family size of six members, a household requires about 3,600 litres (3.6 m^3) of water per month.

The distance between homes and water points ranged between less than 0.5 km and over 3.5 km. About 56 per cent of the respondents travel a distance of less than 0.5 km, while only 1.0 per cent travel over 2.5 km to water points. A majority of the households (85 per cent) make between two and nine trips to water points per day.

On average, each household makes five trips per day to fetch water. The number of trips made to water points among the sampled households ranged between one and 24. The average amount of time spent each day by each household fetching water was 127 minutes (around two hours), with a minimum of six minutes and a maximum of 720 minutes (12 hours). The nature of the terrain between homes and water points was described as steep (47 per cent), gently sloping (41 per cent), and flat (12 per cent). The majority of the respondents (50 per cent) fetch their domestic water in the morning, while 24 per cent and 8 per cent fetch in the evening and afternoon, respectively. However, about 18 per cent fetch water at any time of the day. Fetching was done by adult women (46 per cent), children aged between 12 and 18 years old (31 per cent), children below 12 years old (19 per cent), and hired labour (4 per cent).

The majority of the respondents (89 per cent) did not pay for water – only 11 per cent paid for it. About 77 per cent of the respondents were willing to pay for water and only 23 per cent were unwilling. The reasons for unwillingness to pay for water were that water is a natural free gift from God (29 per cent), it is abundantly available (14 per cent), and is a social good (17 per cent). Other reasons included no income to pay for water (27 per cent) and own water points (10 per cent).

Water is a scarce resource; yet crucial for human survival. This scarcity is linked to climate change, demand that exceeds available water resources, and most importantly unsustainable use of the resource (Molle, 2000; Ogallo, 1996). Many parts of the world, notably the Middle East, are experiencing intense competition over limited water resources. This situation is more serious in shared drainage basins where it is has heightened political conflicts (McCaffrey, 1993). The situation is not any better in Kenya. Over four-fifths of the country is arid and semi-arid and therefore experiences water stress. Competition over water between agricultural, industrial, domestic, and municipal needs has worsened, stretching the ability of the hydrological systems to recover (Orie, 1995; WRI, 1994).

Water for human use is becoming a challenging issue in view of the rapid population growth and increase in economic activities being experienced in Kenya (Kaigai, 1996; Republic of Kenya, 1997). For both domestic and economic purposes, people use more water than is available and contaminate the remainder without spatio-temporal considerations of the effects of their actions for the downstream communities and future generations. This situation is complicated by unsustainable use of water that imposes heavy economic, social, health, and environmental costs (Smith, 1996). Unsustainable use is associated with the viewpoint that water is a free social good and infinite in nature. In treating water as a free good, people expect that it is their right to take as much water as they want and even contaminate the remainder.

Given water's long history as a social good, there is need for demand management instruments if consumers are to use water wisely. The World Bank suggests adequate pricing of water as one of these instruments: for instance, it attempts to bring about efficient use and correct allocation decisions for water management (Moigne *et al.*, 1994; Rogers, 1992). This instrument enforces price elasticity of water demand such that water use is inversely related to the price charged. Appropriately set prices for water tend to ration environmental amenities and discourage environmental deterioration by cutting down on destructive and uneconomical consumption. Appropriate pricing of water attracts conservative use of water resources and catchment areas to ensure the continuous flow of river systems. Guided by this philosophy, people are motivated to protect water catchment areas by practising afforestation, pollution control, and general good land husbandry so that more clean water is available for use.

The majority of people in rural Kenya (about 58 per cent) have no access to potable water despite the government target to provide water to all by the year 2000 (Republic of Kenya and UNICEF, 1998). This shortfall is implicated in many deaths and episodes related to waterborne diseases (Petit, 1994; Republic of Kenya, 1994; Smith, 1996; World Bank, 1996). Efforts by government and non-governmental organizations (NGOs) to initiate water supply projects to address the need have largely been unsuccessful, especially because of inadequate participation by beneficiaries (Gross, Wijk, and Mukherjee, 2001; Narayan, 1995). Beneficiary participation is most important for effective pricing of community water resources.

The ideal price for water needs to come from users through contingent valuation. User interest in water-pricing policies includes fairness of charges, stability, incentives for efficient use, and affordability by low-income users and other vulnerable groups. Water-pricing policies risk failure unless they are sensitive to the needs of all users who have to pay at the rates governed by the policies set (Reiter, 1999). Thus rates other than those coming from the users are likely to reduce access of some users, especially because they are non-affordable, or worse, underprice water in consideration of the economic ability of the beneficiaries (Moigne *et al.*, 1994; World Bank, 1996; Hukka, 1996). Participatory pricing of water should therefore stick to a balance between the highest price users are willing to pay for the resource and the full price of water calculated from marginal cost pricing (Emerton, 1997; Rogers, 1992). This balance ensures that the poor are not deprived of this valuable commodity and at the same time water is not highly subsidized by setting tariffs below operation and maintenance (O&M) cost.

The problem

Kakamega is a well-watered district with a mean monthly rainfall of 157.6 mm. The availability of water at most times of the year is likely to make people take it for granted, resulting in unsustainable use. Households in the district obtain domestic water from various sources located at different distances from their homes. The sources of water and distances covered could to a certain extent determine the quality and quantity of water at household level (Valcurtis, 1986; Drangert, 1996; Smith, 1996). Projects initiated to supply potable water have performed dismally, making accessibility a serious issue among users. Problems that lead to poor performance remain largely undocumented, apart from the underpricing and inefficient collection of water revenue from user groups pointed out by Hukka (1996). This study addresses the following key questions.

- What are the sources of domestic water supply?
- How far are water points from households?

The null hypothesis being tested in this study is that there is no significant difference in the sources of domestic water used by respondents.

Literature review

Access to potable water in most developing countries is still a big problem. This is the case despite access to a safe and also adequate water supply being a universally recognized human right which has special significance for the lives of women and children (UN, 1992; Sharma, 1996; Republic of Kenya and UNICEF, 1998). The poor people in rural areas are the most affected, given that they often pay most for water services and suffer most in terms of health and economic opportunity. As such, lack of overall access to water by the poor is closely associated with their poverty. After recognition of the impacts associated with poor access to water, the world community initiated the International Drinking Water Supply and Sanitation Decade (1981–1990), during which a lot of efforts were made to provide potable water to humanity (Moigne *et al.*, 1994; IWSC, 1994; Narayan *et al.*, 2000). These efforts, as the IWSC (1994) notes, would have been impressive were it not for the fact that during the same period the population of developing countries grew by almost 200,000 people per day. This hampered the noble plan of providing potable water to all people by the end of the decade. Thus the majority of the rural population still depend on traditional sources of water, which for some are located several kilometres away from their homes.

Rosen and Vincent (2001), Dufant (1988), and Valcurtis (1986) observe that in developing countries human porterage is the most common means of transporting water among rural people. This task, which falls mainly to women and children, is arduous, time-consuming, and injurious to health. Essentially, the purpose of improved rural water supply has been to reduce this burden. However, as Valcurtis (1986) notes, the process of bringing water nearer the home has proved a difficult and slow task, and the breakdown rate for new installations is very high. Consequently, most African women are condemned to continue carrying water in the traditional way. It is envisaged, however, that with the participation of the beneficiaries in all stages of water development, including sourcing for funds to cover O&M, accessibility and sustainability of water projects are likely to be improved to relieve women of the burden of carrying water for long distances.

Although the international consensus on access to safe water is generally applicable to all countries, the exact definition and criteria for determining what constitutes access to adequate and safe water are the responsibility of each country (Republic of Kenya and UNICEF, 1998). In Kenya, access to safe water is defined as having reasonable access to a safe water supply including treated surface water and untreated but uncontaminated water such as piped water, roof catchments, borehole water, and protected springs and wells. In some quarters, the government defines good access to water as people being within a distance of one kilometre in urban areas and five kilometres in rural areas away from potable water sources (Republic of Kenya, 1994). Five kilometres to a source of water is a long way considering that the main means of transport available to drawers is porterage. It is not clear, however, why the government accommodates the discrepancy in accessibility to water in urban and rural areas when in all the cases water drawers (women and children) are impacted in the same way.

Rosen and Vincent (2001) give a different dimension of access to water. They define access to water in terms of health, energy, and time costs of collecting the resource rather than just distance. Women and children incur three kinds of costs: health damages resulting from the physical carrying of water; the expenditure of energy on carrying water; and opportunity cost of time spent fetching water. All these elements, which combine to leave African women and children vulnerable to all kinds of misfortune, constitute access to water. The health of women and children who fetch water away from households is threatened in three ways (Collingnon, Bernard, and Mazina, 2000; Dufant, 1988). First is exposure to water-based diseases at the source and diseases with insect vectors at or near the source. Second is exposure to accidents, drowning, attack, and assault on the way to or from the source. And third is skeletal injuries caused by carrying heavy loads repeatedly over long periods of time.

Wendy (1995) and Valcurtis (1986) observe that the time and energy spent by women in collecting water is determined by consumption rate, distance to source, terrain to be traversed, method of transport, queuing time at source, number of consumers in household, and number of people available to carry water. Improving accessibility to water by installing more water points, bringing sources closer to homes, or making transport easier reduces the time and labour involved in hauling water. The advantages of this improved access include:

- releasing time for cultivation, education, income generation, leisure, and childcare
- improving health by increased use of water, less injury from carrying, and reduce energy requirements
- reducing population growth, given that the desire to have children for their labour capacity encourages large families
- stemming the drift to urban areas by improving rural amenities.

The above literature supports the fact that efforts to provide water to users within a reasonable distance of their homes have not been successful in developing countries largely due to rapid population growth and poor management of water supply projects, yet there is need for potable water to alleviate hardships encountered by women and children. This study assessed the accessibility of households to domestic water supply in terms of distance covered, energy expended, and time spent in the task of fetching water.

Research methodology

Kakamega district is one of the seven districts making up Western Province of Kenya. Busia and Siaya districts border the district to the west, Nandi and Uasin Gishu districts to the east, Bungoma and Lugari districts to the north, and Vihiga district to the south. The district lies between longitudes 34° 20′ and 35° 00′ E and latitudes 0° 15′ and 1° 00′ N of the equator. The district covers a total area of 1,930 km^2.

Data used in this study came from two sources. The first was information from secondary (documentary) sources and the second was information from primary sources collected during fieldwork from respondents. A literature search was undertaken to contextualize the research theme in the emerging and contemporary theoretical, empirical, and policy debates on water accessibility. After laying a benchmark from the literature review, the study proceeded to carry out field surveys and interviews on sources of domestic water. This study was mainly based on primary data collected during fieldwork conducted between the months of February and May 2001. The research instruments used consisted of questionnaire schedules, focus group discussions, and key informant interviews. Before the main study, a pilot survey was carried out to pre-test the research instruments and work out modalities of identifying respondents in the selected villages. This pilot survey was carried out by both the researchers and a research assistant to familiarize them with the environment in which they were to work and build trust with local institutions and leadership. After the pilot study, various items in the research instruments that looked ambiguous or irrelevant were eliminated and a final version of the instruments prepared ready for the main study. Focus group discussions (FGDs) were done after interview schedules. During the interview schedules, possible participants at the FGDs were identified based on their ability to discuss issues freely and offer suggestions and/or solutions.

The interviews for this study were conducted among the residents of the former Kakamega district that now consists of Kakamega and Butere/ Mumias districts. The study used multi-stage random sampling whereby random selection started at the division level, then down to location and sub-location, narrowing down to the village, and finally to the respondents' households. First of all, five divisions were randomly selected from the 10 divisions in the study area. The divisions selected were Matungu, Butere, Lurambi, Shinyalu, and Ikolomani. In each of the five divisions, one location was randomly selected. In turn, in each location selected, one sub-location was selected on the same basis. Consequently, in each sub-location selected, two villages were randomly selected and in each village 15 households were also randomly selected for interview. To select the 15 households, village elders of the respective villages compiled a list of names of their subjects from which the households were selected. The village elders helped the researchers and the research assistant in getting to the respondents. In cases where a particular respondent was not found at home, the immediate neighbour to the absent respondent was opted for instead. This was done to avoid instances where the researchers and the assistant were to go to the same home several times without meeting somebody responsible to be interviewed, and also cut down on time-wasting.

The initial stage in data analysis consisted of checking for completeness of questionnaires, verifying the consistency of responses, coding, and data entry into the Statistical Package for Social Sciences (SPSS) program. Analysed data provided answers to the research question and formed a basis for conclusions made on the hypothesis of the study. The data were first subjected to computation of simple statistics such as frequencies, totals, percentages, and means. Further analysis of data involved cross-tabulation to determine emerging trends in responses in relation to age, sex, education level, location, amount of water used, and time spent. The significance test used in this study to test the null hypothesis was a chi-square test at 0.05 significance level.

Results and discussions

Demographic and socio-economic characteristics of the respondents

This study sought views from respondents with a wide range of demographic and socio-economic characteristics. In total, 300 respondents were interviewed, and their characteristics are discussed below.

Sex

The sample population was made up of 72 per cent women and 28 per cent men. This large number of women in the sample was due to the fact that they were readily found at home or working in nearby farms. Even in cases where men were found at home, they summoned female members to respond to the questions on learning that the research was on water. The men argued that it is women who deal with water issues most of the time and they therefore stand a better chance of giving accurate answers. This argument stems from a perception that, traditionally, women and children are always drawers, users, and managers of water, and therefore anything to do with water falls squarely in their jurisdiction. This is, however, a misplaced perception in the contemporary society, where women as much are men are engaged in gainful economic activities and thus need time off from fetching water.

Age

The respondents were well spread throughout the age groups. However, the majority (73 per cent) were aged between 20 and 54, with the dominant age group, 35–39, accounting for 15 per cent of the respondents.

Table 10.1 Age group of respondents

Age group	Frequency	%
15–19	12	4.0
20–24	25	8.3
25–29	31	10.3
30–34	41	13.7
35–39	46	15.3
40–44	27	9.0
45–49	25	8.3
50–54	25	8.3
55–59	23	7.7
60–64	19	6.3
65–69	9	3.0
70+	17	5.7

This age group was dominant because it is the point in time when the majority of people in this area leave their parents and establish their own households. The mean age of the respondents, however, was 42, with the youngest interviewed being 17 and the oldest 82 (Table 10.1).

Household size

The average household size of the sampled households was six members. The smallest households, however, had one member while the largest had 15 members. The majority of the households (95 per cent) had between two and 10 members. The households consisted of extended family with the majority of the members being children.

Level of formal education

Over 78 per cent of the respondents had at least some formal education. About 56 per cent had primary-level education and 19 per cent had secondary-level education, while only 4 per cent had university/college education. However, 21 per cent had no formal education at all (Figure 10.1).

The reason for this composition is probably because the interviews were carried out during weekdays between 8.00 am and 5.00 pm, the time when most of those in employment (with secondary and university/college education) were out on duty while others work and reside in towns. Thus, the majority of those found at home had a low level of education and were mostly engaged in work that kept them around the home.

Occupation of head of household

Heads of households were engaged in a number of activities with farming being dominant, accounting for 49 per cent. Others included business,

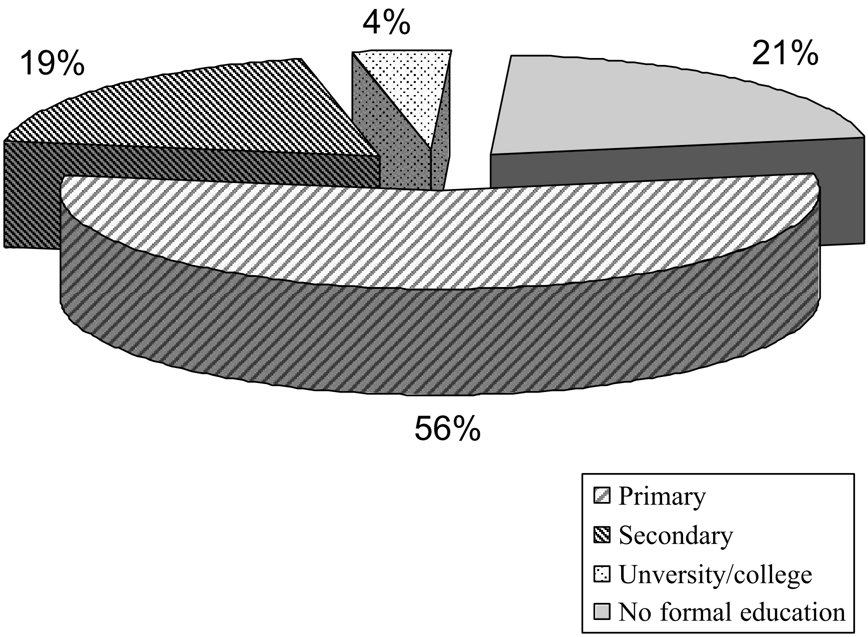

Figure 10.1 Education level of respondents

jua kali (the informal sector), the civil service, and casual labour (Table 10.2)

Although farming is the dominant occupation, most of it consists of subsistence crops. In Matungu, parts of Butere and Lurambi, and Shinyalu sugarcane and some tea farming are practised, respectively. As such what is gained from farming is "hand to mouth", a situation that does not warrant keeping of proper financial records.

Table 10.2 Occupation of head of households

Type of occupation	Frequency	%
Farming	146	48.7
Business	21	7.0
Jua kali	23	7.6
Civil service	21	7.0
Casual labour	15	5.0
Security guard	8	2.7
Unskilled company worker	18	6.0
Other	10	3.3

Table 10.3 Income categories of households

Income category (Kshs)	Frequency	%
<5,000	4	1.3
5,000–10,000	8	2.7
11,000–20,000	29	9.7
21,000–30,000	48	16.0
31,000–40,000	73	24.3
41,000–50,000	19	6.3
>50,000	119	39.7

Household income

Over 39 per cent of the households had an annual income of over 50,000 Kenyan shillings (Kshs). Only 14 per cent reported an annual income of less than Kshs20,000 (Table 10.3).

The issue of income, however, is very sensitive and difficult to estimate. Many people knowingly or unknowingly give wrong figures because they lack records and/or they want to exaggerate their poverty situation so as to benefit in case any aid is available. Unfortunately this study coincided with poverty assessment throughout the country for a poverty reduction strategy paper (PRSP) where some people were exaggerating their poverty situation with the intention of receiving assistance from the concerned bodies. This thus could have hampered getting accurate income figures from the respondents. Despite this scenario, however, every effort was made to obtain realistic income figures.

Sources of domestic water and accessibility

The respondents named their sources of domestic water during both rainy and dry seasons. Over 85 per cent collected their domestic water from springs during dry seasons. This figure dropped to 77 per cent during rainy seasons (Table 10.4), when respondents supplement water from their usual sources with water from roof catchment. Over 74 per cent get at least part of their water from roof catchment during the rainy season.

Roof catchment is a source of water limited to those with permanent and semi-permanent houses. Water collected from grass-thatched houses is considered dirty and cannot be used for any meaningful purpose. Even those with permanent or semi-permanent houses collect only a small amount of water because of inadequate storage containers. The types of containers used – pots, buckets, troughs, *sufurias* (pans) – collect a limited amount of water that is used during the same day, with little available for the next day. Thus, roof catchment as a source of water is still

Table 10.4 Sources of water in rainy and dry seasons

	Rainy season			Dry season		
		%			%	
Source	Frequency	Responses	Cases	Frequency	Responses	Cases
Tap	18	3.5	6.0	16	4.7	5.3
Borehole	11	2.1	3.7	11	3.2	3.7
Spring	231	44.3	77.0	256	74.9	85.3
Well	24	4.6	8.0	17	5.0	5.7
Stream/river	15	2.9	5.0	42	12.3	14.0
Roof catchment	222	42.6	74.0	–	–	–
Total	521	100	173.7	342	100	114.0

undeveloped in this area. Only a few individuals have constructed fibrocement tanks that store reasonable amounts of water.

As noted earlier, springs are the most important source of water across the seasons, accounting for 85 per cent in dry seasons and 77 per cent in rainy seasons. This is mainly because in wet areas such as Kakamega, springs, unlike other sources of water, are naturally occurring and therefore need only a small amount of initial capital for development. Springs form where underground water channels met the surface. Funds are only required to improve them so that they are more efficient and convenient. Protected spring water is considered uncontaminated and can be used without undergoing any significant purification. The only danger of contamination comes when the users ignore hygienic conditions at the water point. During the International Drinking Water Supply and Sanitation Decade (1981–1990), efforts by the government and some NGOs resulted in 690 springs being protected in Kakamega (Republic of Kenya, 1997). The management of these springs through regular maintenance was poor, however, resulting in the collapse of some of them. Using unprotected springs poses great danger to human health in terms of water quality. Such unprotected springs, more often than not, are contaminated by storm runoff that consists of agrochemical residues, household garbage, and even bodies of dead animals. Njenga (1996) reports similar observation of increased incidences of water-borne diseases in rural areas during or shortly after long rains. Thus the World Health Organization (WHO) does not consider water from unprotected springs, wells, streams/rivers, and lakes suitable for human consumption (Rosen and Vincent, 2001).

Only 3.7 per cent use boreholes irrespective of season. This is despite an ambitious plan by the government of Kenya in collaboration with that of Finland through KEFINCO and later on the Community Water

Supply Management Project to provide water by sinking boreholes. The KEFINCO project covered only part of the district, and even in areas which it reached, borehole pumps were stolen, leaving behind ''useless'' holes. The majority of respondents suspected project engineers of having masterminded the stealing of the pumps. The KEFINCO water supply project was basically supply-driven and therefore failed to involve beneficiaries. Supply-driven initiatives do not involve the beneficiaries and are therefore unsustainable.

Wells as a source of water are more common when compared to both tap and borehole: 5.7 per cent and 8.0 per cent use well water during the dry and rainy seasons, respectively. The respondents had either sunk their own wells or used those of their neighbours. However, the use of wells was limited in terms of the purpose for which the water was sought and time of the year. This is because, first, many people who had sunk wells had not taken water from the well for quality analysis, and therefore they were not sure of the quality of the water. Thus, this water was only used for purposes such as washing and bathing. Second, due to lack of either finance or technical know-how or both, most wells do not go down to the zone of the permanent water table, and therefore dry up during the dry season. As such, the users have to look for alternative sources during this time – an event that makes women travel far in search of water. An exception to this is KEFINCO-supported boreholes which, after the stealing of the water pumps, have been turned into wells with a long rope tied to a pail or pulley by which nearby households draw water.

Only 5.3 per cent and 6.0 per cent use a tap as their source of water during dry and rainy seasons, respectively. All the respondents who reported using tap water are found in Emakhatsa village, which borders Bukura Institute of Agriculture that is supplied with tap water. The low use of tap water in Kakamega, like other parts of rural Kenya, is associated with piped water schemes not being as widely spread in rural areas as they are in urban areas. Rural areas benefit from piped water schemes only if they border institutions that are supplied with piped water. The reason for this is that sparse population in these rural areas makes it expensive for water infrastructure expansion to cover a large area. Thus, the government and NGOs operating in such areas prefer other sources of water than piped schemes.

There appear to be differences in the sources of water used by respondents. It is not apparent, however, whether the differences are statistically valid. Thus it is necessary to establish whether the differences are due to chance occurrence or they are real. As such, a chi-square test was applied to verify the null hypothesis that there is no significant difference in the sources of domestic water used by respondents.

The chi-square results ($p = 0.0000 < 0.05$) show that the null hypothesis of no significant difference is not tenable. The differences observed are therefore interpreted as existing within the population and are not due to chance. The differences can be attributed to the fact that people and assisting institutions develop sources of water depending on those most appropriate to a particular area, thus people use different sources of water. In areas with good spring water points, it is a little easier to develop these than any other source, such as tap or borehole. Some areas also present difficult technical and engineering problems in the construction of certain sources of water depending on geological and topographical aspects prevailing in the areas. For instance, granite rock underlying most parts of Ikolomani and Shinyalu does not allow sinking of boreholes, and in such cases an alternative source of water is preferred. This comes out vividly when sources of water are looked at in terms of sub-location or village (Table 10.5).

When sources of water are analysed by sub-location, it emerges clearly that springs and roof catchment are used across all the five sub-locations (Table 10.5). Tap, stream, and well, however, seem to be limited to certain sub-locations, namely Emukaya, Lukose, and Nanyieni, respectively. The use of taps as a source of water in Emukaya is further limited to Emakhatsa village, which borders Bukura Institute of Agriculture that is served with piped water. The residents use this proximity to draw water from the institute. A project started by the institute to extend a piped water scheme to the local people collapsed soon after it was completed. Respondents associated its collapse with misappropriation of funds collected from the beneficiaries.

Another interesting issue is the use of wells in Nanyieni sub-location. This is an area where KEFINCO had made a remarkable impact in terms of the number of boreholes that were sunk. However, due to security lapses embodied in its supply-driven approach, most of the water pumps were stolen. With no money to replace the stolen pumps, the users decided to turn the "remains" of the boreholes into wells either by using a pail with a long rope to draw water or constructing some kind of pulley.

The use of streams/rivers as source of water is found mainly in Lukose sub-location, and specifically in Vigina village (Table 10.5). The respondents explain the use of this source in terms of there being no alternative source in the vicinity. The open-flowing stream water is subject to a lot of contamination, ranging from human dung to decomposing bodies of animals. Within this scenario, the outbreak of water-borne diseases is inevitable. The WHO does not considered untreated water from streams and lakes safe for domestic consumption (WHO, 1996). Hence, the use of water from this source should be limited to uses such as washing and bathing, but not drinking.

Concerning the ownership of water sources, the majority (54 per cent)

Table 10.5 Number of households using different sources of water by sub-location and village

Area		Source of water					
		Tap	Borehole	Spring	Stream/ river	Well	Roof catchment
Ebuchenya		0	6	49	2	3	49
	Mulusi	0	0	14	0	1	11
	Emukangu	0	1	14	0	0	12
	Ebululwe	0	4	11	0	1	14
	Eshibinga	0	1	10	2	1	12
Emukaya		13	1	43	3	3	41
	Emucherera	0	1	14	0	1	13
	Emakhatsa	12	0	2	2	0	10
	Eshianda	0	0	15	0	0	9
	Ekabala	1	0	12	1	2	9
Lukose		4	1	41	10	2	49
	Shihuli	2	0	15	0	1	10
	Shikusi	2	1	8	1	1	13
	Vigina	0	0	3	9	0	12
	Shihumbu	0	0	15	0	0	14
Lirhembe		0	0	50	0	1	55
	Shiseno	0	0	16	0	0	16
	Lirhembe	0	0	21	0	0	19
	Mungabira	0	0	13	0	1	20
Nanyieni		0	3	48	0	15	28
	Ejinjia	0	1	13	0	7	4
	Ebukhutu	0	0	12	0	1	5
	Etete	0	2	9	0	7	10
	Esayangwe	0	0	14	0	0	9

indicated that the community as a whole owned their source of water, while 11 per cent and 17 per cent fetched water from a source of their own and that owned by their neighbours, respectively. Interestingly, 16 per cent argued that water is God's natural gift and as such nobody owns it despite the water point being in someone's land. About 1.3 per cent indicated that their source of water was either owned by a local institution such as church, school, or college or by the government. The question of ownership of water determines to a great extent how people perceive water resources. The perception that water is a natural gift leads to careless and wasteful use of the resource. Humankind can no longer afford to waste water given the prevailing demographic and climatic changes taking place. These changes point to the fact that water is becoming scarce, yet more is required than ever before to serve the rapid population increase and growth in economic activities. Hence this calls for the perception of water as a private property with a scarcity value attached to it.

The amounts of water used by sampled households differed considerable. On average, households used six jerrycans (180 litres) of water per day for domestic purposes (cooking, washing, drinking, bathing). The least amount of water used in a household was one jerrycan (20 litres), while the largest amount reported was 36 jerrycans (720 litres). The average daily per-capita water requirement was about 20 litres. This is within the WHO standard requirement of 20–25 litres/capita/day. Thus, based on average daily per-capita water requirement of 20 litres and average family size of six members, a household needs about 3,600 litres of water per months for domestic purposes. Lifeline water pricing can be based on this statistic so that households whose water requirement goes beyond this limit can be subjected to pricing based on the true value of water.

The distance travelled to water points varied from less than 0.5 km to over 2.6 km. The majority of the respondents (56 per cent) travel a distance of less than 0.5 km, while only 1.0 per cent cover a distance of over 2.6 km to water points (Figure 10.2).

These results show that the majority of respondents (over 55 per cent) are within the distance which the WHO considers convenient. Although

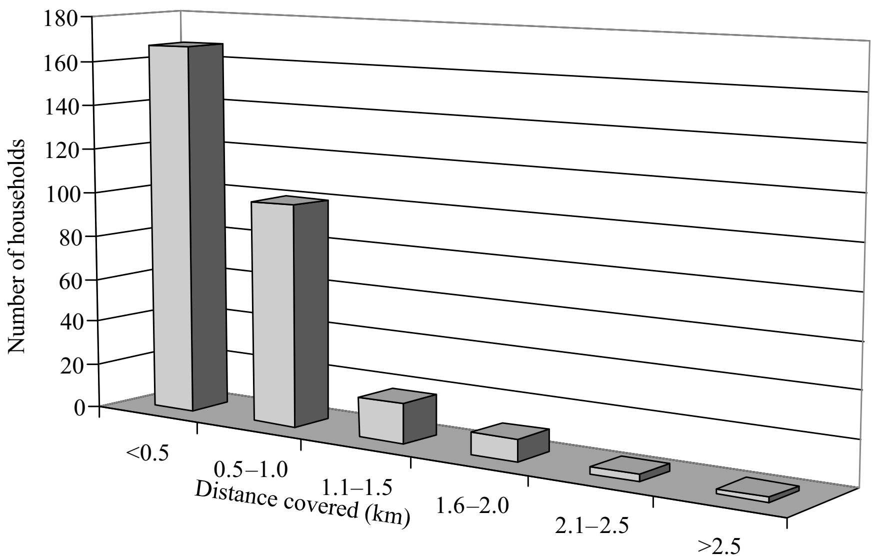

Figure 10.2 Distance covered to water points

studies such as Whittington *et al.* (1990), Mehretu and Mutambirwa (1992), Dufant (1988), and Cairncross and Cliff (1987) show a close relationship between distance travelled and amount of water used in a household, this study does not reveal the same. The amount of water used by each household does not in any way vary inversely or otherwise with distance. This is partly linked to the fact that the majority of the people (86 per cent) are within a distance of less than 1.0 km from water points. This makes the issue of distance to water point somewhat insignificant in this study. People use the amount of water they consider adequate for their daily activities irrespective of whether the water point is less than 0.5 km or 2.0 km away. Thus an inverse relationship between amount of water used and distance covered to water points can only possibly occur in situations where the distance to water point is considerable, maybe over 5.0 km.

Since water points in this study area are far away from homesteads, if access was improved a lot of time women and children spend collecting water could be saved and reallocated to other activities. Even if the inverse relationship between water consumption and distance travelled were true, price elasticity of water demand would contain unnecessary water use, hence saving time and energy and other inconveniences that would result from an increase in the amount used. The Kenyan government considers water within a distance of 1.0 km in urban areas and 5.0 km in rural areas to be within easy reach. But a water point 5.0 km away cannot be said to be within easy reach considering that the main means of transporting water for most rural women is porterage. Hauling water for such long distances, as noted earlier, has many bad health implications for women, leave alone time and energy wasted. As such, the government needs seriously to reconsider its definition of easy access to water in the light of the means of transport of water available to rural women and their economic contributions to the country.

Time spent in collecting water

On average, households make five trips to water points each day. The minimum number of trips made among the sampled households was one, while the maximum was 24. The majority of the households (85 per cent), however, make between two and nine trips. The number of trips to water points depends on a variety of factors, namely:

- amount of water used in a household
- number of people fetching water
- means of transport, e.g. wheelbarrow, bicycle
- amount of water carried per trip, which is a function of the age of the drawer and size of container.

In total, a lot of time is spent in fetching domestic water. On average, sampled households spend 127 minutes (two hours) collecting water. The least amount of time spent on this activity is six minutes, while the maximum time spent is 720 minutes (12 hours). An enormous amount of time spent fetching water does not in any way mean that the resource is scarce, but is due to the difficult terrain (steep slopes) water drawers have to traverse, undeveloped water sources, especially unprotected springs where drawers have to queue and wait for dirt to settle before fetching, and crude methods of drawing water, especially from the wells. Thus, like the number of trips, the amount of time spent in fetching water is a function of amount of water used, number of households using a particular water point, nature of terrain (slope angle), means of transport, distance to water point, and the nature of the water point (i.e. whether well developed or not). The majority of the households (57 per cent) spend between 30 and 120 minutes fetching water every day.

The opportunity cost associated with time spent securing water for domestic use is quite enormous. This fact came out very clearly during focus group discussions where participants had the opportunity to evaluate the lost productivity of time spent fetching water. One female participant pointed out that she spends close to four hours fetching water every day. This time is enough to earn her Kshs50 working as a casual labourer on a neighbour's farm. People working on their own farms, doing business, etc., gave other such estimations. A woman participant who sometimes works at the Mumias Sugar Company as a casual worker gave another spectacular opportunity costing of time. She noted that the company pays them Kshs30 per hour, such that if the three hours she spends every day fetching water were paid at the same rate she would receive at least Kshs90 per day. These examples illustrate how time spent by women fetching water can be turned into productive use if their accessibility to water in terms of distance, time, and energy were improved by developing water from various sources.

It was noted that when time spent on collecting water was drastically reduced, like during the rainy season when roof catchment is used as a source of water, the time saved is spent in more productive activities such as working on farms in the morning and resting and/or doing business in the afternoon. This fact in itself shows that improving accessibility of households to water definitely results in improvement in rural socioeconomic conditions by women using time saved from collecting water to engage in more productive activities.

Water is fetched at different times of the day. Over 50 per cent fetch domestic water in the morning while about 24 per cent fetch their water in the evening (Table 10.6).

The majority prefer fetching water in the morning for two reasons.

Table 10.6 Time of the day respondents collect water

Time of the day	Frequency	% Responses	% Cases
Morning	207	50.1	69.0
Afternoon	32	7.7	10.7
Evening	101	24.5	33.7
Any time	73	17.7	24.3
Total	413	100	137.7

First, in the morning water (especially spring, well, and borehole water) is clear before being disturbed by large numbers of people fetching and animals coming to drink. Second, in the morning drawers are energetic and the sun is not hot. Thus, the first priority in women's daily schedule is given to water, signifying the central role of water in the home and to some extent the difficulty involved in obtaining it at late hours of the day.

The issue of fetching water stands ahead of women's other daily activities. More economically productive activities such as farming come only second after water, a fact that greatly interferes with the socio-economic equations of women and children. This study observed that in some homes children fetch water in the morning before leaving for school and make other trips to water points after they come back from school in the evening. On weekends they first engage in farm work before making several trips to water points to fetch water for the household. This leaves the children exhausted for the rest of the day. This, as noted by Republic of Kenya and UNICEF (1998), interferes with the academic work of children, leading to poor performance and drop-outs in school.

It was interesting to note from this study that the duty of collecting water falls squarely on the shoulders of adult women, both sexes of children below 12 years of age, and female teenagers (13–18 years). About 46 per cent of the respondents reported that adult women did the fetching of water, particularly those married within the household, while 31 per cent indicated that it was the duty of children between 12 and 18 years (Table 10.7). However, the majority of children who fetch water in this age category are female, because male children at this point in time develop the perception that the task of collecting water is the responsibility of women and therefore men are not supposed to do it.

As noted by Wendy (1995), women's great concern with water issues springs logically from their traditional roles. They are generally the ones who obtain water for home, transport, and storage, and then use it for

Table 10.7 Members of the family who fetch water

Member of the family who fetch water	Frequency	% Responses	% Cases
Children below 12 years	90	19.4	30.0
Children aged 12–18 years	143	30.8	47.7
Adult women	212	45.6	70.7
Hired labour	20	4.3	6.7
Total	465	100	155.1

various household purposes. Given this state of affairs, women need to be empowered to address accessibility issues regarding water, and hence improve their socio-economic productivity and health status.

Summary and conclusions

The main purpose of this study was to assess accessibility to domestic water resources in terms of distance and time. As such, this study was guided by two research questions. What are the sources of domestic water supply? How far are water points from households? These research questions gave rise to the specific objective that this study sought to achieve: to establish the major sources of domestic water supply and time/distance covered to water points. The study used both documentary and field-based techniques to collect and analyse required information to achieve the set objective. Interview schedules, key informant interviews, and focus group discussions were used to gather data required for this study. Specifically, an interview schedule based on a prepared questionnaire was used to collect information on sources of water, distance to water points, amount of water used, trips made to water points, and nature of the route to water points.

When the 300 respondents were asked their sources of water during wet and dry seasons, 85 per cent and 77 per cent said they collect their domestic water from springs in dry and rainy seasons, respectively. Over 74 per cent get some of their water during rainy seasons from roof catchment. Water from roof catchment is used to supplement water from other sources such as springs. Less than 10 per cent of respondents reported using other sources of water in both dry and wet seasons. When sources of water were cross-tabulated with sub-location where the respondents were interviewed, it comes out clearly that sources of water such as tap, stream/river, and well were largely restricted to certain sub-locations –

Emukaya, Lukose, and Nanyieni, respectively. However, spring and roof catchment as sources of water are used across all sub-locations. The main sources of water for the people of Kakamega were found to be springs and roof catchment, though the latter as a source of water is not well developed. People lack containers such as tanks in which to collect rainwater, hence a lot of water goes untapped. Other sources of water such as boreholes, wells, and rivers/streams were used at a limited scale and restricted to certain areas.

When respondents were asked who owns their source of water, 54 per cent indicated that it is the whole community while 16 per cent said that water was a natural gift from God and therefore nobody owns it. This view of water as a gift from God and therefore a public good leads to wasteful use and does not favour conservation of the resource. The amount of water used by respondents varied greatly. The water requirements per day per household ranged from one jerrycan (20 litres) to 36 jerrycans (720 litres), depending on the size of the household. On average, respondents use six jerrycans (180 litres) of water per day. Thus, based on average daily per-capita water requirements of 20 litres and average family size of six members, a household requires about 3,600 litres (3.6 m^3) of water per month. On the basis of this statistic, lifeline water pricing can be designed such that households whose water requirement goes beyond this volume are subjected to prices that reflect the true value of water.

The respondents' distance travelled to water points ranged from less than 0.5 km to over 3.5 km. About 56 per cent of the respondents travel a distance of less than 0.5 km while only 1.0 per cent cover a distance of over 2.5 km to water points. On average, households make five trips to water points to fetch water in a day. The trips made to water points in sampled households ranged from one to 24. The majority of the households (85 per cent) make between two to nine trips to water points a day. The average amount of time spent by households on the task of fetching water was 127 minutes (about two hours). The least amount of time spent on this activity was six minutes and the maximum was 720 minutes (12 hours). About 47 per cent of the respondents described the nature of the route to water points as steep, 41 per cent described it as gently sloping, and only 12 per cent described the route as flat. Although the majority (56 per cent) of the people cover a distance which the WHO considers to be convenient, they spend a disproportionate amount of time collecting water due to the difficult terrain (steep slopes) they traverse and undeveloped water points with a very low volume of water coming out, leading to long queues. Thus, accessibility to domestic water in Kakamega is poor in terms of time spent fetching water, difficult terrain, and poor quality of water, especially from unprotected springs and wells.

The majority of the respondents (50 per cent) fetch their domestic water in the morning, while 24 per cent and 8 per cent fetch in the evening and afternoon, respectively. However, about 18 per cent fetch water at any time of the day. The task of fetching was reported by 46 per cent, 31 per cent, 19 per cent, and 4 per cent to be the duty of adult women, children between 12 and 18 years old, children below 12 years old, and hired labour, respectively. Thus improving households' accessibility to domestic water is directly improving the health and socio-economic status of women and children. As such, easy access to domestic water needs to form a critical focus point in poverty reduction and women's empowerment campaigns. Water for the majority of women comes as a first priority in the morning. Other more important activities such as farm work, education for children, and childcare come later on. The reasons given by respondents for fetching water in the morning were to get good-quality water, especially from unprotected springs and rivers/streams, and that as fetching water is a task which requires a lot of energy to climb steep slopes, they prefer morning before being fatigued by other daily chores and before the sun becomes scorching. Therefore, developing water sources by protecting springs and wells and taking tap water and sinking boreholes closer to the people ensures that women (water drawers) engage more meaningfully in important activities such as farm work, education, business, childcare, etc.

Since most of the respondents obtain their domestic water from springs and supplement it with that from roof catchments during the rainy season, there is a need for the government and/or development agencies working on rural water supply, in collaboration with the beneficiaries, to develop these sources of water. This can be done through protecting springs and ensuring environmental sanitation around water points, and enhancing roof-catchment techniques by encouraging and enabling households to obtain storage tanks as opposed to using small vessels such as pails and pots.

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REFERENCES

Cairncross, S. and J. L. Cliff. 1987. "Water use and health in Mueda, Mozambique", *Transactions of the Royal Society of Tropical Medicine and Hygiene*, Vol. 81, pp. 51–54.

Collingnon, P., K. Bernard, and L. Mazina. 2000. "Independent water and sanitation providers in African cities: Full report of a ten-country study", available at www.wsp.org/pdfs/af-providers.pdf.

Drangert, J. O. 1996. "Rural water sources reconsidered: Development perspectives from Sweden and Tanzania", in A. Hjort-af-Ornas (ed.) *Approaching Nature from Local Communities: Security Perceived and Achieved*. Linkoping: EPOS, pp. 15–36.

Dufant, A. 1988. "Women carrying water: How it affects their health", *Waterlines*, Vol. 6, No. 3, pp. 23–25.

Emerton, L. 1997. "Valuing household use of non-timber forest products", in S. A. Crafter, J. Awimbo, and A. J. Broekhoven (eds) *Non-timber Forest Products: Value, Use and Management Issues in Africa, Including Examples from Latin America*. Nairobi: IUCN, pp. 17–24.

Gross, B., C. Wijk, and N. Mukherjee. 2001. "Linking sustainability with demand, gender and poverty: A study in community managed water supply projects in 15 countries", available at www.wsp.org/pdfs/global-Plarepart.pdf.

Hukka, J. 1996. "Rural water supply in Kenya: A case study of the Kenya-Finland western water supply program", in R. Hirji, F. M. Patorni, and D. Rubin (eds) *Integrated Water Resources Management in Kenya*. Nairobi: EDI, pp. 58–67.

IWSC. 1994. *Achievement and Challenges: Water and Sanitation for All*. The Hague: IRC International Water and Sanitation Centre.

Kaigai, N. N. 1996. "An overview of the rural water supply sector in Kenya", in R. Hirji, F. M. Patorni, and D. Rubin (eds) *Integrated Water Resources Management in Kenya*. Nairobi: EDI, pp. 88–97.

McCaffrey, C. S. 1993. "Water, politics, and international law", in P. H. Gleick (ed.) *Water in Crisis*. New York: Oxford University Press, pp. 92–101.

Mehretu, A. and C. Mutambira. 1992. "Time and energy costs of distance in rural life space of Zimbabwe: Case study of the Chiduku communal area", *Social Science and Medicine*, Vol. 34, No. 1, pp. 17–24.

Moigne, G., A. Subramanian, M. Xie, and S. Giltner. 1994. *A Guide to the Formulation of Water Resources Strategy*. Washington, DC: World Bank.

Molle, F. 2000. "Water pricing in Thailand: Theory and practice", available at www.std.cpc.ku.ac.th.delta/deltacp/water_pricing.htm.

Narayan, D. 1995. *The Construction of People's Participation: Evidence from 121 Rural Water Supply Projects*. New York: World Bank.

Narayan, D., R. Chamber, M. K. Shah, and P. Petesch. 2000. *Voices of the Poor Crying Out for Change*. New York: Oxford University Press.

Njenga, N. 1996. "Rural sanitation in Kenya", in R. Hirji, F. M. Patorni, and D. Rubin (eds) *Integrated Water Resources Management in Kenya*. Nairobi: EDI, pp. 80–88.

Ogallo, L. A. 1996. ‘‘Human induced climate changes: Myths or reality’’, in *Environment and Development in Kenya*. Nairobi: Kenya National Academy of Science, pp. 169–194.

Orie, K. K. 1995. ‘‘Legal regime of water allocation and the conservation of aquatic environmental values in Kenya’’, *Journal of Eastern African Research and Development*, Vol. 25, pp. 76–114.

Petit, M. J. 1994. ‘‘The World Bank’s new water resources management policy’’, in World Bank (ed.) *Proceedings of the First Annual International Conference on Environmentally Sustainable Development, Washington DC, 30 September–1 October*. Washington, DC: World Bank, pp. 56–65.

Reiter, S. 1999. ‘‘Transparency and customers’ participation in water pricing policies’’, available at www.bbc.co.uk/nature/animals/news/125news2.shtml.

Republic of Kenya. 1994. *Welfare Monitoring Survey II: Basic Report*. Nairobi: Government Printer.

Republic of Kenya. 1997. *Kakamega District Development Plan 1997–2001*. Nairobi: Government Printer.

Republic of Kenya and UNICEF. 1998. *Situation Analysis of Children and Women in Kenya*. Nairobi: UNICEF.

Rogers, P. 1992. ‘‘Integrated urban water resource management’’, in G. P. O. Obasi (ed.) *Water and the Environment: Development Issues for the 21st Century*. Dublin: UNEP, pp. 7–27.

Rosen, S. and J. R. Vincent. 2001. *Household Water Resources and Rural Productivity in Sub-Saharan Africa: A Review of the Evidence*. Washington, DC: Equity and Growth through Research (EAGER).

Sharma, N. P. 1996. ‘‘The political economy of water resources management in Africa: Choices and tradeoffs’’, in N. P. Sharma (ed.) *Sub-Saharan African Water Resources*. Nairobi: World Bank, pp. 29–36.

Smith, D. 1996. ‘‘Environmental impact assessment and the sustainable supply of water to the poor majority’’, in R. Hirji, F. M. Patorni, and D. Rubin (eds) *Integrated Water Resources Management in Kenya*. Nairobi: EDI, pp. 48–56.

UN. 1992. *Earth Summit Agenda 21*. Rio de Janeiro: UNEP.

Valcurtis, W. 1986. *Women and Transport of Water*. London: Intermediate Technology Group.

Wendy, W. 1995. *Gender Issues Source Book for Water and Sanitation Projects*. Washington, DC: World Bank.

Whittington, D., A. Okorafor, A. Okore, and A. McPhaila. 1990. *Cost Recovery Strategy for Rural Water Delivery in Nigeria*. New York: World Bank.

WHO. 1996. ‘‘Water and sanitation’’, available at www.kenya-wildlife-service.org/death-fl.htm.

World Bank. 1996. *African Water Resources: Challenges and Opportunities for Sustainable Development*. Washington, DC: World Bank.

WRI. 1994. *World Resources: A Guide to the Global Environment*. New York: Oxford University Press.

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Part III

Climate change and catchment modelling: Studies from the headwater regions of Kenya

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11

Methodology for evaluating the regional impact of climate change on water resources

Mwangi Gathenya

Introduction

The most profound global threat facing humanity in this millennium is the prospect of global warming, with serious consequences for water resources. Reports based on results of general circulation models (GCMs) circulated by the Intergovernmental Panel on Climate Change (IPCC) predict that the global mean surface air temperature will rise relative to 1990 by about 2°C by the year 2100 if current greenhouse gases' emission trends continue. Global warming will be associated with changes in wind and rainfall patterns and relative humidity, which would in turn affect water balance components such as surface runoff, evapotranspiration, and soil moisture. By applying the results of climate models to catchment water balance models, it is possible to predict the impact of climate change on the hydrological behaviour of the catchments. In this chapter, a methodology for evaluating the impact of climate change on the water balance of a catchment is presented. Thika catchment, which has an area of 1,852 km^2 and supplies water to Nairobi and Thika towns and to several irrigation projects, is used as an example. LARSIM, a deterministic, physically based macroscale hydrological model, was applied to compute the water balance for the base case. By use of plausible climate change scenarios derived from the results of the various climate models, the climatic input data were perturbed after which the water balance was recalculated. The results of the two calculations are compared. The biggest impact on the water balance components is contributed by a change in precipitation, while temperature and other climate variables result in relatively smaller impacts.

Climate models are used to predict climate change resulting from an increase in greenhouse gases in the earth's atmosphere. These models work with coarse spatial (generally 10^4 km^2) and temporal (annual or seasonal) resolutions, hence their results are not directly relevant for hydrological studies dealing with assessment of the impact of climate change on water resources. One way of determining the sensitivity of hydrological variables to climate change is to create scenarios at the hydrological scale by applying the simulated changes in temperature and precipitation to the observed catchment climate data and running the hydrological model with perturbed data as input (Bultot *et al.*, 1992). In this way, water balance models can be used to investigate the impact of climate change on water resources of smaller river basins (Gleick, 1986, 1987; Miller and Russell, 1992).

The increase in greenhouse gas concentration results in an increase in net radiation and changes in temperature, rainfall, and evaporation. This may affect soil moisture regimes, groundwater recharge, and runoff. The effect of climate change on water resources will affect different countries to different extents. In countries where water is insufficient and population growth is high, the problem will become more acute. Compared to countries like Viet Nam, Ukraine, Mexico, and France where the water supply per person is over 4,000 m^2 per year, Kenya has only 640 m^2 per year. Even without climate change, this water supply will reduce to 170 m^2 per person by the year 2050 as a result of population growth (IPCC, 1996). The water demand for irrigation may increase as a result of climate change (e.g. through increased evaporation).

This study uses LARSIM, a physically based hydrological model, to evaluate the water balance of the Thika catchment in Kenya. Three general circulation models are used to evaluate the likely changes in climate in the Thika catchment that might follow a doubling of carbon dioxide levels in the atmosphere. The impacts of the changes predicted by these GCMs on the Thika water balance are assessed.

Study catchment and database

The Thika catchment lies in the upper Tana catchment between 36° 35′ and 37° 35′ E and 0° 35′ and 1° 10′ S. It is about 40 km north-west of Nairobi and about 100 km south of the equator. The Thika River springs from the eastern slopes of the Nyandarua ridges and flows south-eastwards through Thika town. About 100 km downstream of Thika town, the Thika River flows into the Tana River on which seven hydroelectric

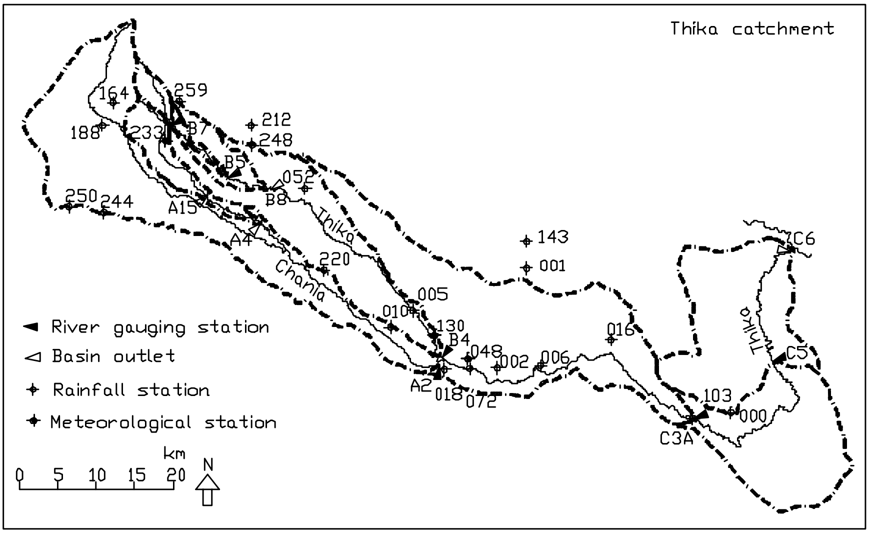


Figure 11.1 Thika catchment showing the gauging, rainfall, and meteorological stations

power dams are located (Figure 11.1). The Chania River which also flows from the slopes of Nyandarua joins the Thika River near Thika town.

The elevation of the catchment ranges from about 1,030 m above sea level at the basin outlet up to 3,906 m above sea level at the headwaters of the Chania River, with an average of 1,700 m above sea level (Figure 11.1). The catchment is characterized by altitude-dependent agro-climatic zones (humid to semi-arid), varying land uses (forest, small-scale farms, plantations, and savanna), and different soil types. Annual rainfall varies from about 800 mm at an altitude of about 1,100 m to about 2,600 mm at an altitude of 2,600 m (NCC, 1986; KMD, 1984; Jaetzold and Schmidt, 1983). The annual potential evapotranspiration increases from about 1,250 mm at an altitude of 2,400 m to about 1,800 mm at an altitude of 1,100 m.

The population densities range from 100 persons/km^2 in the lower, drier region to over 500 persons/km^2 in the coffee- and tea-growing zone. The small-scale farmers of this area are mainly dependent on rain-fed agriculture and limited irrigation of horticultural crops, whereas the large-scale farms (coffee, pineapples) are under supplemental irrigation, especially during the dry months of January to March and August and September.

The gauging, rainfall, and meteorological stations are shown in Figure 11.1. This study is based on a four-year series (1967–1970) of daily climatic data (rainfall, temperature, wind speed, sunshine, humidity) obtained from the Kenya Meteorological Department and streamflow data obtained from the Ministry of Water. The climatic data were collected at Kimakia Forest Station (Station 233 in Figure 11.1, at 2,440 m above sea level) and Thika Horticultural Research Station (Station 130, later replaced by Station 048, both at about 1,500 m above sea level). Rainfall data for the 20 rainfall stations shown in Figure 11.1 were also obtained. Although most of the hydrometeorological stations in this catchment have historical data series of over 30 years' duration, only four years were used for the simulation due to gaps in one or more of the required data series.

Streamflow data for the six gauging stations B7, B5, B4, A2, C3A, and C5 shown in Figure 11.1 were obtained. Station C6 is the basin outlet and has no measured data. The classification of the soils of the catchment according to the FAO system was obtained from the exploratory soil map of Kenya compiled by Sombroek, Braun, and Pouw (1982), and corresponding soil physical properties were obtained from Batjes (1997). Topographic information was obtained from topographic sheets at a scale of 1:50,000 obtained from the Survey of Kenya. These maps also contained some information on land use, e.g. forest boundaries. Additional land-use information was derived from aerial photos, satellite images, and field observations.

Description of water balance model

The large-area runoff simulation model (LARSIM) developed in Karlsruhe, Germany, to serve as a component of a hydrology-atmosphere model within the framework of the Baltic Sea Experiment, BALTEX (Bremicker, 1998) was applied in the Thika catchment. The model was modified to fit Kenyan climatic and land-use conditions (Gathenya, 1999). LARSIM is a continuous, conceptual, deterministic, distributed-parameter model. It uses climatic data (precipitation, air temperature, wind speed, relative humidity, and sunshine), land-use parameters (effective height of vegetation, surface or stomata resistance, leaf area index, and albedo), and soil information (available water capacity of the root zone) to simulate surface runoff (direct runoff, interflow, base flow), actual evapotranspiration, interception, and soil moisture. It can be used to evaluate changes in water balance arising from climate or land-use change.

The daily soil water balance of the root zone is a major component of LARSIM. The basin was divided into grid elements. The percentage area of different land-use types within each grid element was determined. For each land-use type within an element, available water capacity of the root zone W_m was estimated based on the soil water holding, hydrologically active root depth, and soil depth. The soil moisture content of the root zone storage W_o has a value of zero at wilting point and a maximum value W_m at field capacity. The initial moisture content of the root zone within an element is provided as an input to the model. From the inputs and outputs within a 24-hour period (daily time step), a daily water balance of the root zone is maintained such that:

$$W_o(t+1) = W_o(t) + P(t) - INCP(t) - ETR(t) - QS_D(t) - QS_I(t) - QS_G(t)$$

where $W_o(t+1)$ is water content of the root zone storage at time $t+1$, $W_o(t)$ is water content of the root zone storage at time t, P(t) is precipitation or snow-melt, INCP(t) is intercepted precipitation, ETR(t) is actual evapotranspiration, $QS_D(t)$ is lateral drainage into the direct runoff reservoir, $QS_I(t)$ is lateral drainage into the interflow reservoir, and $QS_G(t)$ is vertical drainage (percolation) into the groundwater reservoir.

Observed precipitation is corrected for systematic errors by means of a simple factor. The capacity of interception storage depends on the land use and is described in LARSIM as a function of leaf area index, in accordance with Dickinson (1984), as follows:

$$K_{Inz} = 0.2 \cdot LAI$$

where K_{Inz} is capacity of interception storage in millimetres and LAI is leaf area index in m^2/m^2.

After the storage is filled up, any rain falls directly to the ground. The interception storage is emptied through evapotranspiration at a rate equivalent to potential evapotranspiration. Actual evapotranspiration, which is responsible for soil moisture depletion, is calculated using the Penman-Monteith formula.

The simulation of surface, subsurface, and groundwater runoff follows the approach of the Xinanjiang model first developed in 1973 (Zhao and Liu, 1995). Todini (1996) later modified it. Based on the rainfall and soil moisture deficit, three runoff components, direct runoff, interflow, and groundwater, are generated from three fictitious soil layers and become inputs for three respective reservoirs. Inflow into the direct runoff reservoir is calculated as a function of rainfall P and soil moisture deficit $(W_m - W_o)$. An important model parameter denoted by b (soil moisture curve shape parameter), which relates the spatial distribution of soil moisture to the proportion of saturated areas in the form of a probability distribution function, is used.

An empirical relationship is used to calculate the lateral subsurface drainage (interflow) and groundwater runoff from the soil as a non-linear function of the water content of the root zone storage.

Model application and calibration

LARSIM was applied to compute the water balance of the Thika catchment. The test catchment was divided into square grid elements each having an area of 4 km^2. The runoff from each element flows in one of eight possible directions into the next element in the river-routing sequence through a channel whose length was assumed to be 3 km. The flow direction was chosen so as to reproduce the natural drainage system as closely as possible. A hydrological approach (Williams, 1969) was used to route channel flow through the drainage system in all channel segments apart from those in source elements (elements that have no incoming drainage channel). The outflow from each element is first determined and then routed down the channel to the main basin outlet. For each element there were seven possible land-use types: forest, tea zone, coffee zone, coffee plantation, urban, dry savanna, and plantation and thornbush savanna.

Eight model parameters were calibrated by trial-and-error method using the four-year data series (1967–1970) until a good fit between measured and calculated streamflows at each of the six gauging stations was obtained. The values of the coefficient of determination (R^2) obtained for the gauging stations B7, B5, B4, A2, C3A, and C5 were 0.84, 0.77, 0.86, 0.90, 0.64, and 0.75 respectively (Gathenya, 1999).

Evaluation of climate change impact for Thika catchment

The results from three general circulation models (GCMs) given in IPCC reports (IPCC, 1990, 1995), those of Cubasch and Hegerl (1996), and those of ECHAM (European Centre for Medium Range Weather Forecasting model, Hamburg) were used to estimate how the climate of the Thika catchment is most likely to change following a doubling of carbon dioxide concentration in the atmosphere ($2 \times CO_2$ scenario). Since the Thika catchment is much smaller than the grid elements used in climate models, the results are not expected to be very accurate. This problem is compounded by the difficulty in predicting future climate in the tropics, especially for variables like rainfall, where inter-model discrepancies are significant. The changes in temperature and rainfall for the $2 \times CO_2$ scenario compared to the $1 \times CO_2$ scenario obtained using three high-resolution models are presented in a map of the whole world by the

IPCC (IPCC, 1990). The base year is 1990 with its corresponding CO_2 concentration ($1 \times CO_2$), and CO_2 is assumed to double by the year 2100.

The temperature changes obtained from the IPCC (IPCC, 1990) for the $2 \times CO_2$ scenario for the Thika catchment lie between 0°C and 2°C with only small seasonal variations being indicated. Cubasch and Hegerl (1996) indicate changes in temperature of 2°C to 4°C for the period 1880 to 2050. These results are based on simulations with the ocean-atmosphere model ECHAM3 coupled to the LSG (large-scale geostrophic). If the aerosol effect is considered, the temperature increases are less by 1°C (Cubasch and Hegerl, 1996).

The changes in rainfall shown in the IPCC (1990) maps range from −1 to 1 mm/day depending on the model. This gives a change in annual rainfall of about ±30 per cent for an average annual rainfall of 1,200 mm. From the results of Cubasch and Hegerl (1996), a change in rainfall of −5 mm/day for the period 1880 to 2050 is obtained for the region around the Thika catchment. This corresponds to a change in annual rainfall of −9 per cent. The results of Cubasch *et al.* (1995) suggest that a reduction in rainfall is more likely for the Thika catchment than an increase. From these results, it is clear that precise estimates of the magnitude of expected changes cannot be obtained and that even the direction of the changes for the Thika catchment is uncertain.

Global warming is expected to affect the relative humidity and wind patterns. It can be proved from physical relationships that a change in air temperature of 1°C would cause a change in relative humidity of about 7 per cent if the air has an initial temperature of 20°C. It is assumed here that the change in relative humidity depends only on temperature, which is not the case for a complex system such as the atmosphere.

The most comprehensive predictions of climate change for the Thika catchment were obtained from results of the ECHAM4 model, which are presented in Figure 11.2. The results were obtained on 16 July 1998 and are for a grid point that lies closest to the catchment (coordinates 36.5625° E, 1.3953° S). This point is located on the Ngong hills near Nairobi, about 70 km south-west of Thika town. The resolution of this model is 312 km × 312 km at the equator. The predictions apply for the period 2010–2039 and are based on the period 1961–1990. They incorporate greenhouse gas effects as well as effects of sulphate aerosols.

Effect of climate change on the water balance of the Thika catchment

The approach used in this study to investigate the effect of climate change on the water balance components involved establishing climate change

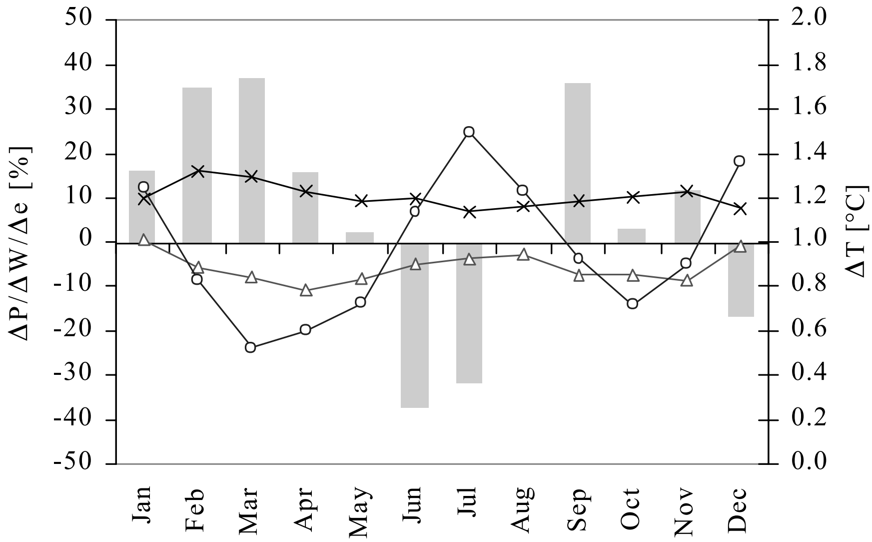


Figure 11.2 Predicted climate change for Thika catchment based on results of ECHAM4 climate model

scenarios based on results of the GCMs just described. The 10 scenarios that were considered are:

- base run: no climate perturbations
- P−15%: a constant 15 per cent decrease in precipitation
- P+15%: a constant 15 per cent increase in precipitation
- T+2°C: a constant increase in temperature of 2°C
- RH−15%: a constant 15 per cent decrease in relative humidity
- RH+15%: a constant 15 per cent increase in relative humidity
- W−15%: a constant 15 per cent decrease in wind speed
- W+15%: a constant 15 per cent increase in wind speed
- WC: worst-case scenario – a combination of scenarios 2, 4, 5, and 8
- ECHAM: climate change according to results of ECHAM4. The average annual changes represented by this scenario are P+11%, T+1°C, RH+11%, and W−6%. The changes are not constant over the year.

A constant change in climate means that change was applied uniformly throughout the simulation period. For scenario 10, the changes were varied from month to month but were constant within a month. The results of the impact of these climate changes on the water balance of the entire catchment averaged over the four-year simulation period are presented in Table 11.1. The impacts of climate change are to some extent dependent on the model structure and on the assumptions made. The

Table 11.1 Effect of changes in the climate variables on the water balance of the Thika catchment

Scenario		Description
1	Base run	No climate perturbations.
2	P−15%	A constant 15% decrease in precipitation.
3	P+15%	A constant 15% increase in precipitation.
4	T+2°C	A constant increase in temperature of 2°C.
5	RH−15%	A constant 15% decrease in relative humidity.
6	RH+15%	A constant 15% increase in relative humidity.
7	W−15%	A constant 15% decrease in wind speed.
8	W+15%	A constant 15% increase in wind speed.
9	WC	Worst-case scenario. This is a combination of scenarios 2, 4, 5, and 8.
10	ECHAM	Climate change according to results of ECHAM4. The average annual changes represented by this scenario are P+11%, T+1.0°C, RH+11%, and W−6%. The changes are not constant over the year.

results comply at least qualitatively with physical relationships, but the precision of the values presented here cannot be claimed.

Actual evapotranspiration ETR increases when rainfall P, wind speed W, and temperature T increase and increases when relative humidity RH decreases. The runoff depth h_Q decreases when temperature T and wind speed W increase and increases when rainfall P and relative humidity RH increase.

If one examines the effect of a change in the individual climate variables, one notices that a change in P has the greatest impact, especially on the runoff depth h_Q. For instance, if P is increased by 167 mm (P+15%), h_Q increases by 126 mm (+31 per cent) while the ETR increases by 39 mm (+5 per cent). The impact of a change in temperature T or relative humidity RH on ETR is smaller, and on h_Q significantly smaller. The effect of a change in T and RH on h_Q is only 20 per cent of the effect of P. The effect of a change in wind speed W is the smallest of all. When P changes, the fraction ETR/P and h_Q/P also changes. The fraction ETR/P and h_Q/P changes from 0.65 and 0.36 respectively for the base run to 0.71 and 0.30 respectively for the P−15% scenario. In a drier climate, the proportion of water lost to evapotranspiration is higher than in a wetter climate.

When P increases, the change in P denoted by ΔP is distributed over ΔETR and Δh_Q in the ratio 1:3, and when P decreases the ratio of the distribution is 1:2. When RH and W decrease, the corresponding absolute changes in h_Q and ETR are smaller than when RH and W increase. The change in ETR in millimetres due a change in T, RH, and W is balanced by a change in h_Q of similar magnitude but opposite in sign.

As expected, the worst-case scenario WC has the biggest impact on h_Q. The runoff h_Q reduces by 158 mm, which is a reduction of 40 per cent compared to the base run, or an extra 10 percentage points when compared to the scenario P−15%. ETR remains practically the same. The other extreme is the scenario ECHAM, whereby ETR remains almost the same as in the base run and the increase in P (+11 per cent on average) leads to a 29 per cent increase in h_Q.

The Thika catchment has varied agro-climatic zones, from a humid tea zone to a semi-arid area. It is expected that the impacts of climate change would be different for the different agro-climatic zones. Therefore an investigation of the impact of a change in rainfall (ΔP) for each of five subcatchments of the Thika catchment was carried out where the components of total runoff depth, i.e. direct runoff, h_{QD}, interflow, h_{QI}, and groundwater flow, h_{QG}, were separately examined. Only the scenarios associated with a change in P are considered. The results are presented in Table 11.2. The subcatchments B4 and A2 lie on the upper half of the catchment where rainfall is high and evapotranspiration is low (humid to semi-humid). The forest zone is also found here: 15 per cent of B4 and 45 per cent of A2 are under forest. The subcatchments C3A-C5 (refers to area draining through C5 but excluding the area draining through C3A) and C5-C6 (refers to area draining through C6 but excluding the area draining through C5) lie in the lower half of the Thika catchment where the rainfall is low and evapotranspiration is high (semi-humid to semi-arid) and the land cover is savanna-type vegetation with some areas under plantation farming. The results for the subcatchments B4 and C3A-C5 serve to illustrate the most important findings. The results for catchment C6, representing the entire catchment, are also given for comparison.

The results for the base run show that the water balance of the humid zone differs from that of the semi-arid zone. On average, for the entire catchment 65 per cent of the rainfall evaporates and 35 per cent runs off. Evaporation accounts for 55 per cent and 77 per cent of rainfall in B4 and C3A-C5 respectively. Direct runoff, h_{QD}, interflow, h_{QI}, and groundwater flow, h_{QG}, comprise 62 per cent, 22 per cent, and 17 per cent of the total runoff for the whole catchment. For the subcatchments, the proportion of h_{QI} remains approximately constant while the proportions of h_{QD} and h_{QG} change significantly following a change in precipitation. More of the runoff appears as direct runoff in the drier zone (78 per cent) as compared to the humid zone (47 per cent). Consequently, the proportion of groundwater runoff is lower in the drier zone than in the humid zone (4 per cent compared to 23 per cent). More rainfall is lost to evapotranspiration (77 per cent) in C3A-C5 than in B4 (56 per cent). That means

Table 11.2 Changes in the water balance for subcatchments B4 and C3A-C5 and for the whole catchment C6 as a result of climate change for various scenarios

Scenario	P (mm)	ΔP (mm)	ETR (mm)	ETR/P (%)	h_Q (mm)	h_Q/P (%)	ΔETR (mm)	ΔETR (%)	Δh_Q (mm)	Δh_Q (%)
Base run	1,117	0	724	64.8	403	36.1	0	0.0	0	0.0
P+15%	1,284	+167	762	59.3	529	41.2	+39	+5.3	+126	+31.2
P−15%	949	−168	674	71.0	288	30.3	−50	−6.9	−115	−28.6
T+2°C	1,117	0	746	66.8	382	34.2	+22	+3.0	−21	−5.1
RH−15%	1,117	0	756	67.7	372	33.3	+33	+4.5	−31	−7.6
RH+15%	1,117	0	695	62.2	430	38.5	−29	−4.0	+27	+6.8
W−15%	1,117	0	714	63.9	412	36.9	−10	−1.4	+9	+2.3
W+15%	1,117	0	731	65.4	396	35.5	+8	+1.0	−7	−1.8
ECHAM	1,237	+120	728	58.8	518	41.9	+4	+0.6	+115	+28.5
WC	949	−168	719	75.8	245	25.8	−5	−0.7	−158	−39.2

	Scenario	P (mm)	ΔP (mm)	ETR (mm)	ΔETR (mm)	h_Q (mm)	Δh_Q (mm)	h_{QD}/h_Q (%)	h_{QI}/h_Q (%)	H_{QG}/h_Q (%)
Subcatchment B4	Base run	1,470		821		655		47	30	23
	P−15%	1,250	−220	772	−49	488	−167	43	31	26
	P+15%	1,691	+221	861	+46	833	+178	49	30	21
	WC	1,250	−220	838	+17	425	−230	45	29	26
	ECHAM	1,605	+135	819	−2	791	+136	49	30	21
Subcatchment C3A-C5	Base run	735		563		182		78	19	4
	P−15%	624	−111	510	−53	125	−57	76	20	4
	P+15%	845	+110	603	+40	251	+69	76	21	3
	WC	624	−111	530	−33	105	−77	79	17	4
	ECHAM	835	+100	576	+13	268	+86	75	22	3
C6	Base run	1,117		724		403		62	22	17
	P−15%	949	−168	674	−50	288	−115	59	21	19
	P+15%	1,284	+167	762	40	529	+126	63	23	14
	WC	949	−168	719	−5	245	−158	62	19	19
	ECHAM	1,237	+120	728	+4	518	+115	62	24	14

that the drier zone receives less rainfall and more of it runs off or evaporates, leading to less groundwater recharge and less water available for plants.

Following a change in rainfall, the subcatchments also react differently. The scenarios P+15% and P−15% yield absolute changes in annual rainfall amount of between 221 mm (B4) and 110 mm (C3A-C5). The corresponding changes in evapotranspiration ΔETR show relatively small differences in the two subcatchments, e.g. ΔETR ranges from +46 mm to −53 mm in absolute terms and from +7 per cent to −10 per cent as a percentage. A change in P results in considerable change in runoff depth h_Q (Δh_Q is 60–80 per cent of ΔP). The absolute values of ΔP are of course greater in the humid zone than in the semi-arid zone. For all subcatchments, a reduction in P results in a decrease in proportion of runoff, i.e. h_Q/P of about 5–6 per cent. The same change also applies for an increase in P. Therefore a decrease in rainfall will affect the runoff in the drier zone more than in the wetter zone. An analysis of the runoff components shows that a change in P does not significantly affect the proportions h_{QD}/P, h_{QI}/P, and h_{QG}/P.

Since ΔP for the scenarios P−15% and WC are equal, the resulting impacts are also roughly equal in magnitude. The same case applies for the scenario ECHAM and P+15%. The scenario WC would cause a reduction in h_Q of −230 mm (−35 per cent) for B4 and a negligible increase in evapotranspiration ETR of +17 mm (+2 per cent). The reduction in h_Q of 167 mm for subcatchment B4 for the scenario P−15% is considerably smaller than for the scenario WC. For scenario WC, ETR for subcatchment B4 increases even though the moisture supply is lower. This is due to the effect of increased wind speed and temperature and reduced air humidity. For the subcatchment C3A-C5, ETR diminishes for the two scenarios P−15% and WC. This shows that moisture availability is the main factor limiting ETR in this zone. Other factors such as wind speed, humidity, and temperature play a lesser role. The scenario ECHAM is a "best-case" scenario with positive effects on the water balance. In subcatchment B4, runoff h_Q increases by 136 mm (+21 per cent) and ETR remains practically the same. In subcatchment C3A-C5, h_Q increases by 86 mm (+47 per cent). Investigations of the effect of climate change on soil moisture were done. They showed that the proportion of days (in percentages) during which the soil storage was empty ($W_o = 0$) for a representative element in subcatchment B4 changed from 6 per cent for the base case to 5 per cent and 10 per cent for scenarios ECHAM and WC respectively. For subcatchment C3A-C5 the percentages were 45 per cent for the base case and 40 per cent and 56 per cent for scenarios ECHAM and WC respectively. The semi-arid zone again responds more strongly to climate change than the humid zone.

Conclusion

A water balance model was used to illustrate how the impact of climate change on water resources can be investigated. Climate change scenarios were based on results of various GCM simulations. The water balance for the base run was compared with the water balance computations under the climate change scenarios. A climate change associated with a change in precipitation will have a significant impact on runoff and evapotranspiration. Changes in other climatic variables have relatively smaller impacts. Drier catchments respond differently to climate change compared to wetter catchments. The results obtained serve to illustrate the direction of expected impacts. The magnitudes of the changes have less meaning due to uncertainty associated with results of GCMs. The results also depend on assumptions made in developing the water balance model.

REFERENCES

Batjes, N. H. 1997. ''A world dataset of derived soil properties by FAO-UNESCO Soil Unit for global modeling'', *Soil Use and Management*, Vol. 3, pp. 9–16.

Bremicker, M. 1998. ''Aufbau eines Wasserhaushaltsmodells für das Weser- und das Ostsee-Einzugsgebiet als Baustein eines Atmosphären-Hydrologie-Modells'', PhD dissertation, Institute of Hydrology, Albert-Ludwigs University, Freiburg.

Bultot, F., D. Gellens, M. Spreafico, and B. Schadler. 1992. ''Repercussions of a CO_2 doubling on the water balance – A case study in Switzerland'', *Journal of Hydrology*, Vol. 137, pp. 199–208.

Cubasch, J. and G. Hegerl. 1996. *Vorhersage von Klimaänderungen unter Anwendung von Modellen der allgemeinen Zirkulation*, Vol. 56a. Munich: Institute for Water Engineering, University of German Federal Armed Forces.

Cubasch, J., J. Waszkewitz, G. Hegerl, and J. Perlwitz. 1995. ''Regional climate changes as simulated in time-slice experiments'', *Climate Change*, Vol. 31, pp. 273–304.

Dickinson, R. E. 1984. ''Modelling evapotranspiration for three dimensional global climate models'', in J. E. Hansen and T. Takahashi (eds) *Climate Processes and Climate Sensitivity*, Geophysical Monograph Series No. 29. Washington, DC: AGU.

Gathenya, J. M. 1999. ''Einsatz von Wasserhaushaltsmodellen zur Wasserbewirtschaftung am Beispiel des Thika-Chania-Gebietes in Kenya'', PhD dissertation, Institute for Hydraulic Engineering and Water Management, University of Kaiserslautern, Kaiserslautern.

Gleick, P. H. 1986. ''Methods for evaluating the regional hydrologic impacts of global climate changes'', *Journal of Hydrology*, Vol. 88, pp. 99–116.

Gleick, P. H. 1987. ''The development and testing of a water balance model for the climate impact assessment: Modelling the Sacramento basin'', *Water Resources Research*, Vol. 23, No. 6, pp. 1049–1061.

IPCC. 1990. *Climate Change, the IPCC Assessment*, report prepared by Working Group 1, Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC. 1995. *Summary for Policy Makers: The Science of Climate Change*, IPCC Working Group 1. Cambridge: Cambridge University Press.

IPCC. 1996. *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group 2 to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Jaetzold, R. and H. Schmitt. 1983. ''Natural conditions and farm management information. Part B – Central Kenya (Rift Valley and central provinces)'', in *Farm Management Handbook of Kenya*, Vol. II. Nairobi: Ministry of Agriculture.

KMD. 1984. *Climatological Statistics for Kenya*. Nairobi: Kenya Meteorological Department.

Miller, B. A. and G. L. Russell. 1992. ''The impact of global warming on river runoff'', *Journal of Geophysical Research*, Vol. 97, pp. 2757–2764.

NCC. 1986. *Third Nairobi Water Supply Project Vol. III Final Report*. Nairobi: Nairobi City Commission Water and Sewerage Department/Howard Humpreys Kenya.

Sombroek, W. G., H. M. H. Braun, and B. J. A. Pouw. 1982. *Exploratory Soil Map and Agroclimatic Soil Map of Kenya, 1980, Scale 1:1,000,000*, Exploratory Soil Survey Report No. E1. Nairobi: Kenya Soil Survey.

Todini, E. 1996. ''The ARNO rainfall-runoff model'', *Journal of Hydrology*, Vol. 175, No. 1, pp. 339–382.

Williams, J. R. 1969. ''Flood routing with variable travel time or variable storage coefficient'', *Transactions of the ASAE*, Vol. 12, No. 1, pp. 100–103.

Zhao, R. J. and X. R. Liu. 1995. ''The Xinanjiang model'', in V. P. Singh (ed.) *Computer Models of Watershed Hydrology*. Colorado: Water Resources Publications.

12

Analysis of surface runoff from headwater catchments in upper Ewaso Ng'iro North drainage basin in Kenya

Japheth O. Onyando and Mathew C. Chemelil

Introduction

Flood hydrographs are a result of accumulation of direct runoff over a catchment and concentration of the same in stream channels, where they are measured to determine their magnitude and time distribution. Direct runoff occurs after removal of abstractions such as infiltration, depression storages, and interception from storm rainfall. The magnitude of the abstractions depends on the rainfall and catchment characteristics such as soil types, vegetation cover, topography, and antecedent soil moisture. Thus, more abstractions for the same storm rainfall imply less direct runoff and vice versa, and hence low and high magnitude of flood hydrographs respectively.

From the interrelationship between a flood hydrograph and direct runoff, the magnitude and time distribution of the former, which is the one usually measured in stream channels, can be used to derive the magnitude and time distribution of the latter, which is usually spread over the entire catchment, especially for small catchments (Chow, Maidment, and Mays, 1988). Since the magnitude of the flood hydrographs depends on the catchment characteristics, it is therefore implied that changes in catchment characteristics can be detected by flood hydrograph characteristics. For example, a catchment with good vegetation cover will tend to have low peak hydrographs and longer duration of flows while a catchment with less cover will have high peaks and shorter duration of flow. Of the two flood characteristics, the latter causes more destruction to the catchment in terms of soil erosion, sedimentation, depletion of water resources, and other related environmental degradation. Thus studies of flood hydrograph characteristics in relation to catchment characteristics are necessary for appropriate catchment management.

To accomplish studies on flood hydrographs, data for the same are needed. Such data are usually obtained from measurements taken by automatic water-level recorders which plot the time variation of river stages. The river stages are converted into flood hydrographs using rating equations. However, it is worth noting that automatic water-level recorders are expensive to acquire and maintain and therefore most streams, particularly in developing countries such as Kenya, do not have them. The few which exist are sited in research catchments, and after the end of the research they become non-operational over time due to inadequate maintenance. Examples of such catchments in Kenya are Sambret and Lagan on the upper slopes of the Sondu River basin, the Kimakia catchment on the upper slopes of the River Tana, and the Mathare and Iuni catchments on the upper slopes of the River Athi.

Since flood hydrographs are required for analysing changes in catchment characteristics for appropriate catchment management, and they are not available in adequate quantities for this purpose, alternative methods for generating the data need to be sought. One possible way of achieving this is the use of rainfall-runoff models. These models have physical and conceptual parameters which need to be determined before they can be used to generate flood hydrographs. One rainfall-runoff model, which was used in this study, is the Nash-SCS model, which is a combination of the Soil Conservation Service (SCS) curve number model (Chow, Maidment, and Mays, 1988) for estimation of abstractions and the Nash cascade model (Shaw, 1996) for routing flood hydrographs. Like other conceptual models, the Nash-SCS model has both physical and conceptual parameters which need to be determined prior to its application. The determination of these parameters requires geomorphological data and rainfall-runoff data. Such data were obtained from small catchments located at the headwaters of the Ewaso Ng'iro drainage basin in Kenya. These catchments are currently under the Laikipia research programme and have the relevant data for model calibration, hence their selection.

In calibrating the Nash-SCS model, the physical parameters of the model were derived through spatial analysis of catchment characteristics using geographical information systems (GIS), while the conceptual parameters were optimized by using the Schuffled complex evolution (SCE-UA) algorithm of Duan, Sorooshian, and Gupta (1992). In this calibration process, observed flood hydrographs were used to countercheck the estimated ones from the model, and the results showed that the model performed reasonably well in the five catchments.

The study area

The study area is located on the headwaters of the Ewaso Ng'iro drainage basin. This basin is drained by the River Ewaso Ng'iro, with its source in Mount Kenya, and flows north-eastwards through the Lorian Swamp. The lower reaches of the river traverse the semi-arid areas of north-eastern Kenya, where annual rainfall varies between 500 mm and 700 mm. A large extent of the headwaters, although at a higher altitude, receives low rainfall due to the leeward nature of this part of Mount Kenya (Kohler, 1987). A small portion of the upstream rivers of the Ewaso Ng'iro fall in agro-climatic zones I and II, subhumid and humid zones respectively, with corresponding mean annual rainfall being 1,000–1,600 mm and 1,100–2,700 mm (Braun, 1982). Figure 12.1 shows the location of the catchment and the seven agro-climatic zones of Kenya. As shown in the figure, the semi-humid, subhumid, and humid zones, which are the major headwater areas, are only about one-third of the total area of the country.

The upstream network of the River Ewaso Ng'iro is shown in Figure 12.2. The selected streams for the study are magnified in the enlarged portion of the map. About 19 river gauging stations exist in this area. However, those whose complete data were made available during the time of the research are AR-Lower Ituri, AQ-Mid Ituri, AP-Lower Teleswani, A3-Naromoru North, and A4-Naromoru South.

The altitude of the study area is about 2,450 m above sea level, with mean annual temperatures of less than 12°C which decrease towards the top of Mount Kenya (Braun, 1982; Berger, 1989). The natural vegetation of this area is dry and moist forest, which becomes moister with increasing altitude. The area has soils of loam to clay loam, clay loam to clay, and clay types.

Direct runoff generation processes

Direct runoff comprises surface runoff and subsurface storm flow, which contribute towards flood hydrographs. The surface runoff component is composed of Hortonian overland flow and Beston and Dunne surface runoff. Hortonian overland flow occurs when rainfall intensity exceeds the infiltration capacity of the soil. Dunne surface runoff occurs when

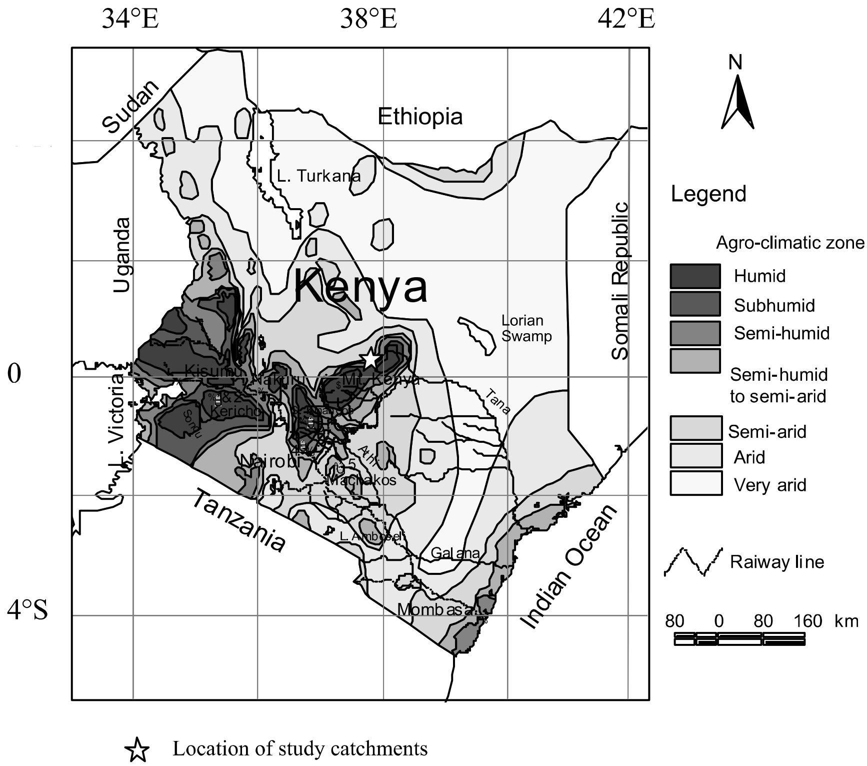


Figure 12.1 Map of Kenya showing catchment location and the agro-climatic zones

rain falls on saturated areas which are caused by an intersection between surface topography and the water table. The Beston type of surface run-off is generated from partial areas. The existence of the three surface runoff generation mechanisms and the possibility of dominance of some mechanisms over the others depend on the catchment and rainfall characteristics. These include antecedent conditions, rainfall intensities and duration, soil characteristics, topography, and land use. Freeze (1980) summarized the coexistence of these runoff mechanisms in a catchment and the environmental changes affecting them (Figure 12.3).

A comparison of Hortonian and Dunne overland flow mechanisms shows that the former is more common on upslope areas while the latter is prevalent in areas near valley bottoms. Further to this, Hortonian overland flow is more common in hill slopes where surface hydraulic conductivities are lower, while Dunne overland flow dominates areas where water tables are shallowest. As shown in Figure 12.3, in arid to

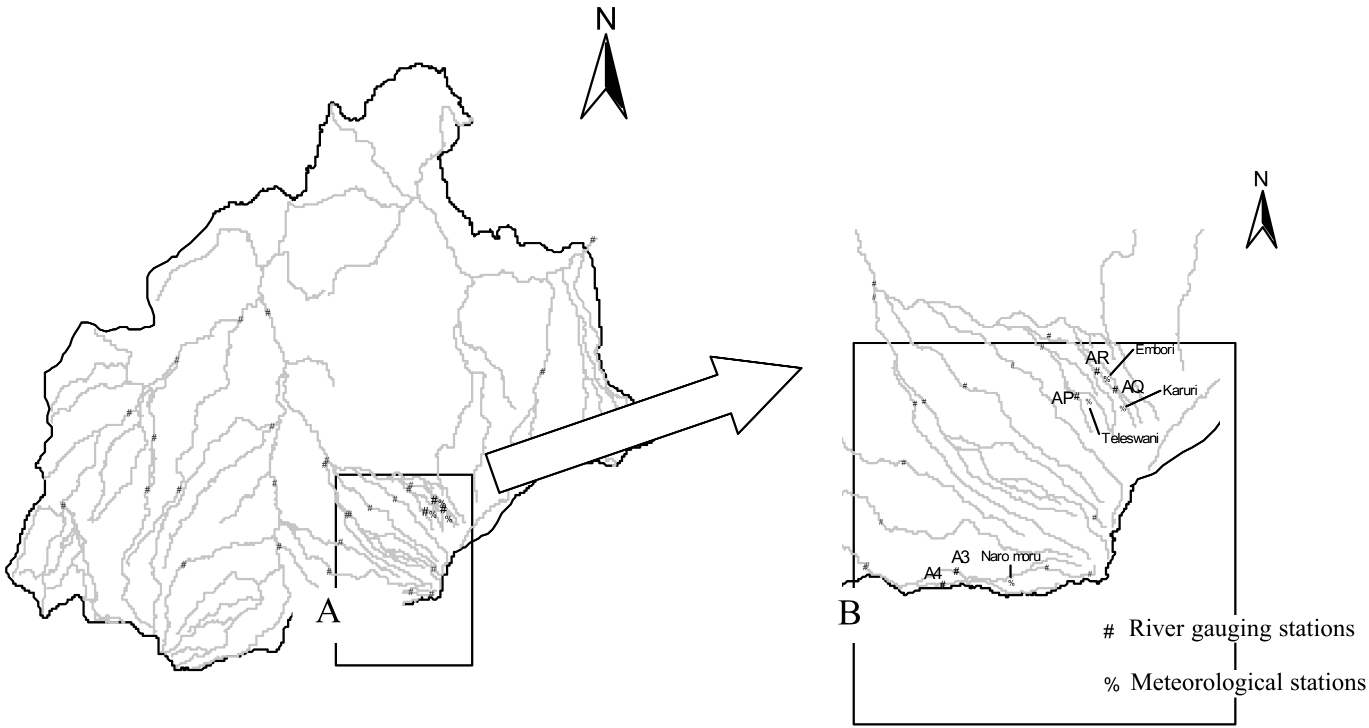


Figure 12.2 Upstream of River Ewaso Ng'iro showing the study catchments

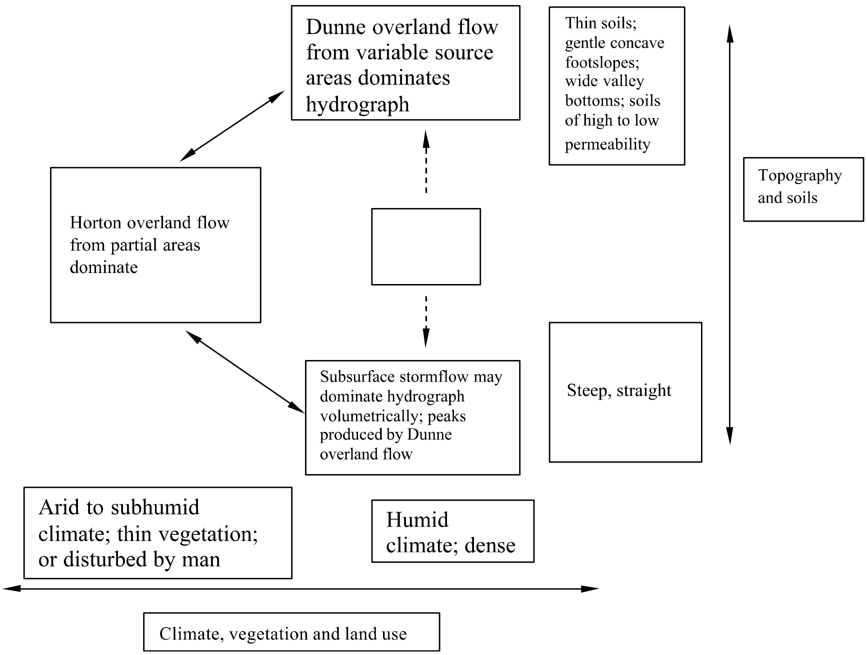


Figure 12.3 Schematic illustration of the occurrence of various runoff processes in relation to their major environmental controls

subhumid climate with thin vegetation Hortonian overland flow dominates regardless of topography and soil types. In humid climate with dense vegetation, Dunne surface runoff dominates in thin soils, concave footslopes, wide valley bottoms, and less permeable soils. From these runoff mechanisms, and the fact that tropical rainfall events are very intense, it is more likely that Hortonian overland flow forms a significant component of direct runoff in headwater areas in Kenya. Thus a model which simulates Hortonian overland flow is more likely to give representative results, hence the selection of the Nash-SCS model. The schematic structure of this model and the mathematical formulations are presented in the next section.

The Nash-SCS rainfall-runoff model

The Nash-SCS model shown in Figure 12.4 was used to accomplish the present study. The model has two components, namely the SCS curve

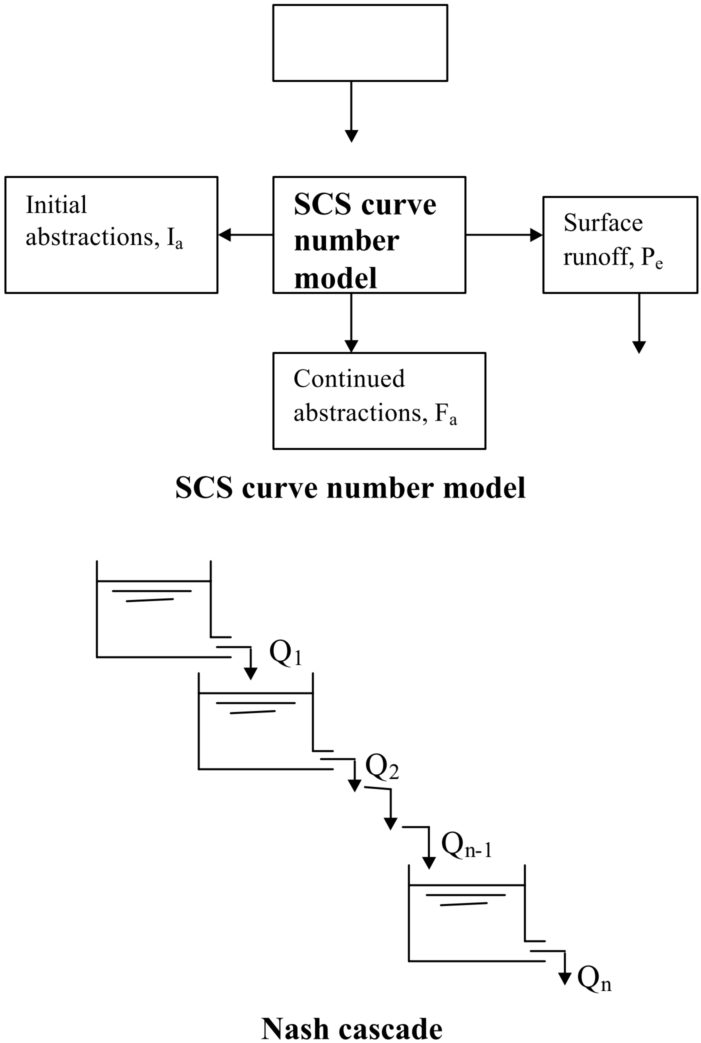


Figure 12.4 Schematic structure of Nash-SCS model

number model for rainfall excess estimation and the Nash cascade model for runoff routing.

In the Nash-SCS model the surface runoff component is simulated using the SCS curve number model through removal of initial abstractions (interception and surface retention) and continuing abstractions (infiltration). This component model is formulated based on the assumption that the continuing abstractions are less than or equal to some potential maximum retention, S. Another assumption is that the actual runoff, P_e, is less than or equal to the potential maximum $(P - I_a)$. From these assumptions, the mathematical expression of the model is derived based on the hypothesis that the ratios of the two actual quantities to the potential ones are equal (equations 1 and 2):

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \tag{1}$$

$$P = P_e + I_a + F_a \tag{2}$$

where P is rainfall depth (mm), P_e is surface runoff (mm), I_a is initial abstraction (mm), S is potential maximum retention (mm), and F_a is continuing abstraction (mm). Combining equations 1 and 2 and solving P_e results in the SCS curve number basic equation (equation 3):

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{3}$$

An empirical relationship exists between I_a and S (Chow, Maidment, and Mays, 1988). This is expressed as equation 4:

$$I_a = \lambda * S \tag{4}$$

where λ is a parameter of the empirical relationship. By substituting I_a in equation 3, the surface runoff P_e can be expressed in terms of P and S only (equation 5):

$$P_e = \frac{(P - \lambda * S)^2}{P + (1 - \lambda) * S} \tag{5}$$

The potential maximum retention, S, can be expressed through a dimensionless parameter, the curve number, CN (equation 6), which is adapted from Maidment (1993):

$$S = \frac{25400}{CN} - 254 \tag{6}$$

The values of CN depend on catchment characteritics such as land use, soil types, and antecedent soil moisture conditions. In hydrologic literature, curve numbers are stated for average soil moisture levels and can either be single or several depending on the heterogeneity of a catchment. For soil moisture conditions other than the average, that value of soil moisture is used to adjust the mean curve number to reflect the soil moisture status of the catchment at the time under consideration. In the classical curve number procedure, only two soil moisture levels apart from the mean level are used to represent the antecedent catchment wetness and subsequently to adjust the mean curve number. These two conditions represent dryness and wetness of a catchment. For all three conditions, the general soil moisture ranges can be found in hydrologic texts (Chow, Maidment, and Mays, 1988; Maidment, 1993). The adjustments for dry and wet conditions proceed as in equations 7 and 8:

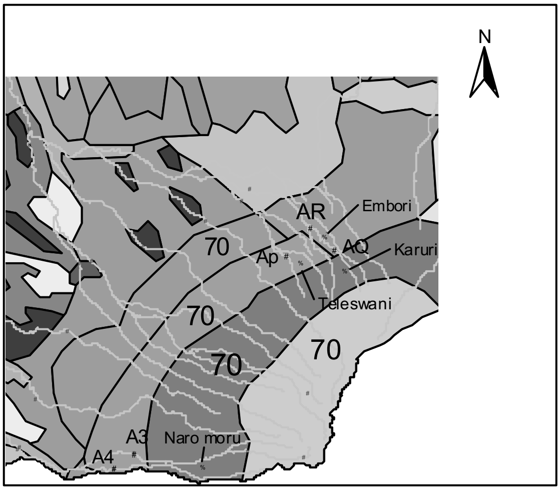
$$CN(I) = \frac{4.2 * CN(II)}{10 - 0.058 * CN(II)} \tag{7}$$

$$CN(III) = \frac{23 * CN(II)}{10 + 0.13 * CN(II)} \tag{8}$$

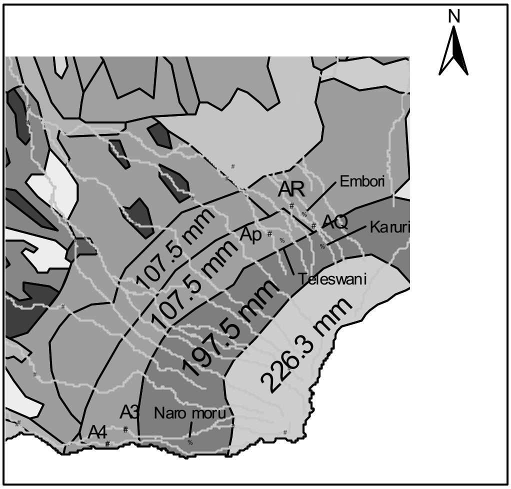
where $CN(I)$ is the curve number of dry conditions, $CN(II)$ is the curve number of average moisture conditions, and $CN(III)$ is the curve number of wet conditions. As indicators of soil moisture condition, the three discrete curve numbers are not sufficient to represent the antecedent soil moisture conditions in a catchment since the soil moisture changes continuously and not discretely. The same sentiments have been echoed by Muzik and Chang (1993), Hjelmfelt (1991), and Tsihrintzis and Sidan (1998). To overcome this problem, a correction factor is presented in equation 9 for adjusting the curve number to represent other soil moisture conditions on a continuous scale (Ott, 1997). This is a better procedure than the classical one, since it gives continuous values for curve numbers.

$$CN_{bf} = \begin{cases} \dfrac{1000}{\frac{1000}{CN(II)} + \frac{CF_s}{25.4}} & \text{for} \quad CN(II) < 100 \\ 100 & \qquad\quad CN(II) = 100 \end{cases} \tag{9}$$

The correction factor of average antecedent soil moisture, CF_S, was derived from mean yearly and mean five-day antecedent precipitation indices. In the present study, this correction factor was treated as a parameter and optimized for every storm event. CN_{bf} is then the corrected curve number.



Spatial distribution of the parameter *CN*



Spatial distribution of the parameter S_m

Figure 12.5 Spatial distribution of the physical parameters *CN* and S_m across the study catchments

Routing of the flow in the Nash-SCS model was achieved using the Nash cascade model, which is expressed as shown in equations 10 and 11:

$$h(t) = \frac{1}{k\Gamma n}\left(\frac{t}{k}\right)^{n-1} e^{-(t/k)} \tag{10}$$

$$Q(t) = \int_0^t h(t-\tau) * P_e(\tau) * d\tau \tag{11}$$

where $h(t)$ is the response function at time t (h^{-1}), n is number of linear reservoirs in the cascade, $Q(t)$ is direct runoff rate in units similar to P_e, and k is the storage constant (h). The two component models form the Nash-SCS model, which has four parameters, namely CN, λ, n, and k. The derivation of these parameters is presented in the next section.

Derivation of model parameters

Among the four parameters, one of them, CN, is physically based and was determined through processing catchment characteristics using GIS. The other three are conceptual parameters and were determined through optimization. The determination of the physical parameter CN was achieved through overlaying hydrologic soil data and land-use data, while the storage capacity S_m was determined from the product of root depth of the vegetation and porosity (Figure 12.5). The values of root depth were derived based on guidelines from Pfueztner (1990). The spatial analysis of these geomorphologic data was made possible with the help of GIS. The values of the two physical parameters so derived are shown in Table 12.1.

After deriving the physical parameters, the conceptual parameters were determined through calibration with the help of optimization algorithms (Duan, Sorooshian, and Gupta, 1992). A split-sampling method was used in the calibration process, where the 40 rainfall and runoff

Table 12.1 Derivation of the physical model parameters CN and S_m

Soil type	Land use	Soil group	*CN* for average condition	Total porosity	Field capacity	Effective porosity	Root depth (mm)	S_m (mm)
Loam	Forest	C	70	0.451	0.270	0.181	1,250	226.3
Clay loam	Forest	C	70	0.476	0.318	0.158	1,250	197.5
Clay	Forest	C	70	0.482	0.396	0.086	1,250	107.5

Table 12.2 Optimized conceptual parameters of the Nash-SCS model

	Predicted parameters				Time lag	
Catchment	I_a	λ	n	k	Predicted	Observed
AR-Lower Ituri	4.93	0.028	3.66	1.21	4.42	3
AQ-Mid Ituri	5.30	0.025	3.48	1.43	4.98	3
AP-Lower Teleswani	6.14	0.032	4.23	0.98	4.15	3
A3-Naromoru North	3.80	0.019	3.69	1.72	6.35	4
A4-Naromoru South	4.53	0.023	4.37	1.18	5.16	4

events from the five catchments were split into two sets in every catchment. One set was used for calibration and the other for validation. In the calibration process, the Nash and Sutcliffe efficiency, *EFF* (Nash and Sutcliffe, 1970), was used as an objective function and the optimized combination of parameters was reached when the value of *EFF* approached 1.0. This efficiency criterion is usually employed in single-event studies like the present case, as recommended by the ASCE Task Committee (1993). It is expressed mathematically by equation 12:

$$EFF = \frac{\sum_{i=1}^{m}(Q_{oi} - Q_{av})^2 - \sum_{i=1}^{m}(Q_{oi} - Q_{si})^2}{\sum_{i=1}^{m}(Q_{oi} - Q_{av})^2} \qquad (12)$$

where Q_{oi} is measured runoff, Q_{si} is simulated runoff, Q_{av} is average measured runoff, m is number of observations, and *EFF* is Nash and Sutcliffe efficiency.

The resulting parameters from the optimization process are shown in Table 12.2, which also includes the parameter I_a, a function of *CN* and the maximum storage capacity derived through overlaying land use and soil coverages. In the same table, predicted time lags obtained as a product of n and k are also shown, together with the observed time lags for the respective catchments.

Results and discussion

Having determined both physical and conceptual parameters as outlined in the previous sections, simulations were carried out using these parameters and data from all the five catchments. Figure 12.6 shows simulated

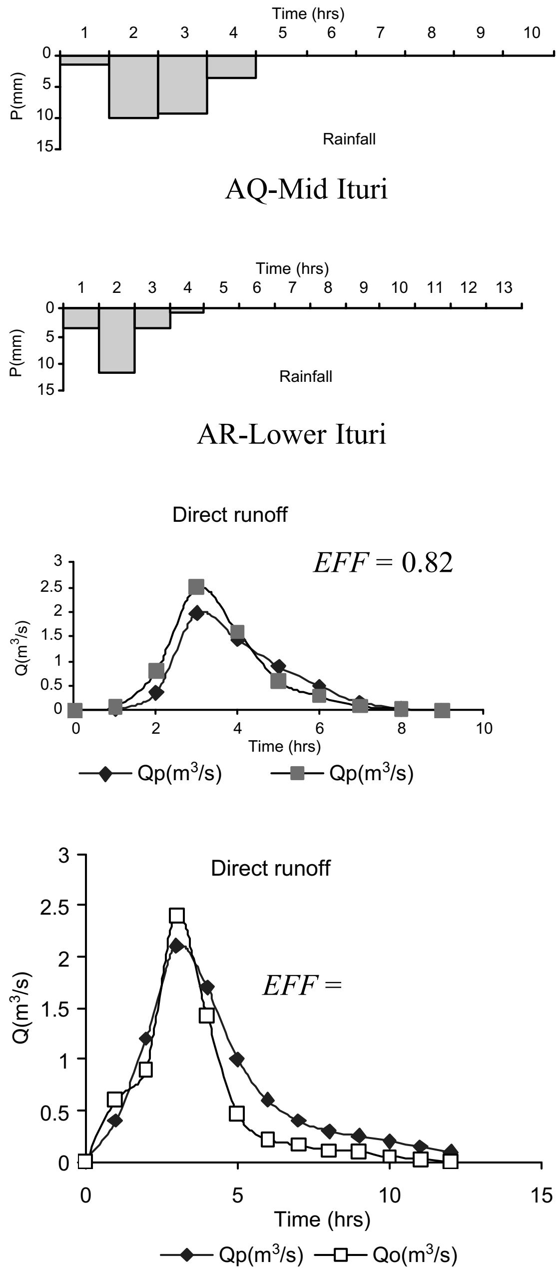


Figure 12.6 Typical observed and predicted hydrographs using Nash-SCS model for catchments AR-Lower Ituri and AQ-Mid Ituri

Table 12.3 Mean values of Nash and Sutcliffe efficiency, *EFF*, for the five catchments

Catchment	1.1.1. EFF
AR-Lower Ituri	0.68
AQ-Mid Ituri	0.76
AP-Lower Teleswani	0.73
A3-Naromoru North	0.72
A4-Naromoru South	0.70

hydrographs alongside observed ones from two typical events from AR-Lower Ituri and AQ-Mid Ituri catchments.

As shown in the diagram, a comparison between observed and simulated hydrographs indicates that the simulations were satisfactory. This follows from visual inspection of the hydrograph parameters of time to peak, duration of flow, peak discharge, and hydrograph shape. Apart from visual inspection, statistical assessment was also carried out for further confirmation of the accuracy of the results using the efficiency *EFF* of Nash and Sutcliffe (1970) as recommended by the ASCE Task Committee (1993). The mean values of the efficiency *EFF* for the five catchments are shown in Table 12.3.

As shown in Table 12.3, the mean value of *EFF* is about 0.7. For a perfect fit, *EFF* equals 1.0, while values of *EFF* close to zero show that the model is performing no better than the mean of observed data (ASCE Task Committee, 1993). Thus with an *EFF* of 0.7 it can be said that the model is performing reasonably well in simulating flood hydrographs.

The validity of the results, on the other hand, is determined by investigating if a relationship exists between the optimized parameters and the relevant catchment characteristics. Through this relationship it can be deduced whether the model is reflecting the local conditions. Considering the parameter of runoff generation, λ, it indicates the proportion of the potential maximum retention, which becomes initial abstraction, I_a. The values of I_a determined as a product of λ and S showed minimal variation across the five catchments (Table 12.2). This is possible because the soil types and land use of these catchments from which S was derived are more or less evenly distributed across the five catchments. The same distribution is thus reflected in the values of the derived physical parameter I_a.

The parameters n and k for routing the direct runoff are verified using their product, which is the time lag. This is the time between the centroid of the excess rainfall hyetograph and the direct runoff hydrograph.

Measured values of this parameter can be obtained from observed data and then compared with predicted time lags (see Table 12.2). This table shows that the predicted mean time lags are greater than the observed ones by one hour on average. This indicates there is slight overestimation of the combination of the two parameters n and k. However, the trend of the mean time lags across the five catchments is the same for both observed and predicted values. This shows that the two parameters are reasonably valid, but further adjustment may be necessary to improve their fitting.

Conclusion and recommendation

The results of this study have shown that by combining the SCS curve number model for runoff generation and Nash cascade model for runoff routing, a conceptual rainfall-runoff model, the Nash-SCS model, is developed which can satisfactorily simulate flood hydrographs. Both component models, the SCS curve number model and the Nash cascade model, have been used elsewhere in temperate regions with reasonable success. However, within the tropics their application is not widespread, hence the need for testing them in this region as well. The positive test results obtained in the present study show the potential of this model for flood hydrograph generation in the humid tropics.

It is worth noting that parameterization plays a pivotal role in satisfactory performance of a model. The use of GIS made it possible to derive the physical model parameters reasonably from the catchment characteristics. With the help of optimization algorithms, the conceptual parameters were also reasonably determined. These methods of determining physical and conceptual parameters have made it possible to apply the Nash-SCS model satisfactorily for flood hydrograph simulation, thus they can be recommended for the same use with other models for flood hydrograph estimation.

Although the flood hydrographs were reasonably simulated by the model, the estimated conceptual parameters, especially the routing ones, were slightly over- and under-predicted, as shown by the comparison between the observed and predicted time lags. This discrepancy is reflected in the *EFF* value, which was less than 1.0 in all the five catchments. However, through more optimization runs, better values of *EFF* and therefore the conceptual parameters, which can correlate well with catchment characteristics, can be derived. That way the model can be more effectively adapted to local conditions, and if more gauged catchments are analysed then extrapolation of the model to ungauged catchments for flood hydrograph simulation can be readily achieved.

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REFERENCES

ASCE Task Committee. 1993. ''Criteria for evaluation of watershed models'', *Journal of Irrigation and Drainage Engineering*, Vol. 119, No. 3, pp. 429–442.

Berger, P. 1989. *Rainfall and Agroclimatology of the Laikipia Plateau, Kenya*, African Studies Series, Vol. 7. Berne: Geographica Bernensia and Geophysical Society of Berne, University of Berne.

Braun, H. M. H. 1982. *Agro-climatic Zone Map of Kenya, 1:1,000,000*. Nairobi: Kenya Soil Survey, Ministry of Agriculture.

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. *Applied Hydrology*, international edition. New York: McGraw-Hill.

Duan, Q., S. Sorooshian, and V. Gupta. 1992. ''Effective and efficient global optimisation for conceptual rainfall-runoff models'', *Water Resources Research*, Vol. 28, No. 4, pp. 1015–1031.

Freeze, R. A. 1980. ''A stochastic-conceptual analysis of rainfall-runoff processes'', *Water Resources Research*, Vol. 16, No. 2, pp. 391–408.

Hjelmfelt, A. T. 1991. ''Investigation of curve number procedure'', *Journal of Hydraulic Engineering*, Vol. 117, No. 6, pp. 725–735.

Kohler, T. 1987. *Landuse in Transition*, African Studies Series, Vol. 5. Berne: Geographica Bernensia and Geophysical Society of Berne, University of Berne.

Maidment, D. R. (ed.). 1993. *Handbook of Hydrology*. New York: McGraw-Hill.

Muzik, I. and C. Chang. 1993. ''Flood simulation assisted by GIS'', in *HydroGis 93: Application of Geographic Information Systems in Hydrology and Water Resources Management*, IAHS Publication No. 211. Wallingford: IAHS, pp. 531–540.

Nash, J. E. and J. V. Sutcliffe. 1970. ''River flow forecasting through conceptual models. Part I: A discussion of principles'', *Journal of Hydrology*, Vol. 10, pp. 282–290.

Ott, M. 1997. ''Investigation to determine regionally valid hydrographs. The case of South Bayern area'', Report 5. Kaiserlautern: Department of Water Resources Management and Construction, University of Kaiserslautern.

Pfuetzner, B. 1990. *Generalized Techniques for Computer-supported Development, Fitting and Practical Application of Catchment Models*, Vol. 49. Dresden: Institute for Water Resources, University of Dresden.

Shaw, E. M. 1996. *Hydrology in Practice*, 3rd edn. London: Chapman and Hall.

Tsihrintzis, V. A. and C. B. Sidan. 1998. ''Modelling urban stormwater runoff processes using the Santa Barbara method'', *Water Resources Management*, Vol. 12, pp. 129–166.

13

Digital image analysis and GIS database design of Lake Bogoria area, Kenya: Three-dimensional modelling for slope evaluation

Simon Mang'erere Onywere

Introduction

Lake Bogoria is one of the Ramsar sites (No. 1097) of wetlands of international importance in Kenya. It is centred at latitude 0° 20′ 24″ N and longitude 36° 04′ 48″ E, with an altitude of 985 m, water surface area 27.97 km^2, mean depth 5.4 m, and shoreline length 42.24 km. The lake is a narrow trough angled between the fault-fragmented Kipngatip Plateau and Lake Bogoria fault scarp at the foot of the west down-faulted steps from the Laikipia escarpment, which is 1,280 m above the lake.

The lake contains highly saline waters, attributed to solution of peralkaline and natro-carbonate and metasilicate-rich volcanic ashes in the water, recirculation of hot alkaline groundwater, and high evaporation from the closed basin. There is recrystallization of the alkaline salts, leading to formation of salt-impregnated sediments at the lake. The lake is replenished and sustained by the River Waseges, and features high enthalpy steaming and boiling springs and geysers, sometimes under pressure. Torfeson (1987) interprets deep fracture zones as being caused by vertical migration of fluids. Clarke *et al.* (1990) postulate a hydraulic connection between Lake Bogoria and the Menengai geothermal prospect with rain-fed thermal waters. The meteoric waters cross in from the Laikipia Plateau down the Marmanet escarpment, and from the Bahati fracture zone to the south (Onywere *et al.*, 2000). Since there is a shallow intrusive magma body interpreted by Ebinger *et al.* (1989) at the axis of the Rift Valley, the surrounding rock is hot, providing heat for the meteoric waters.

The lake water supports the growth of blue-green algae and tiny crustaceans, and the lake has significant ornithological interest with 135 species of birds. Of significance are the 1 million plus lesser flamingo (*Phoenicopterus minor*) – the largest single concentration in the world. These are attracted to the lake seasonally, depending on the abundance of the algae on which they feed. The terrain around the lake is covered by sparse vegetation of shrub, bush, and occasional grass. These support among other animals buffalo, zebra, impala, and the last herds of greater kudu (*Tragelaphus strepsciseros*) remaining in Kenya. The southern shore of the lake is covered by scattered acacia-ficus and fig-tree woodland. Semi-tropical vegetation, dry thorn bushes, and deciduous vegetation cover the deep valleys in the escarpments, whereas thick bushes are found over the Laikipia Plateau and the upper extents of the Marmanet escarpment.

Statement of the problem and research justification

Lake Bogoria is a tourist destination – one of the main economic mainstays of the country – thanks to the flocks of flamingoes, the geysers, and the scenic beauty of the landscape. The lake environment also provides for the immediate needs of the Jemp and Tugen natives who rely on its natural resources for their food. There is a worrying trend of land-cover destruction reported throughout the country, and in particular exemplified by the Kenya Wildlife Services (KWS) reports on the destruction of the Mount Kenya, Imenti, and Ngare Ndare forests (Gathaara, 1999). This is impacting negatively on the Marmanet forest catchment and the water systems. The research aims to assess the land-cover degradation and the morphotectonic control on the surface processes impacting on Lake Bogoria.

The BBC has reported incidences of flamingo mortality at the lake, with major episodes in 1993, 1995, and 2000 (BBC, undated). Research done on the liver and kidney tissue of dead flamingoes identifies organochlorines and heavy metals as the leading causes of the deaths. These chemicals find their way into the lake from water systems over nearby farms. The other lake affected is Lake Nakuru, where other sources of pollution include industrial effluents from the municipality (Kenya Wildlife Service, undated). The farms in the region use large quantities of fertilizers, pesticides, and agrochemicals, which are washed down into, for example, Lake Bogoria through the River Waseges. The algae at the lake are sensitive to the pollutants, nutrients, eutrophication, and siltation, and unless the lake is protected it remains threatened.

Understanding the morphotectonic dynamics of the surface processes and land-use impacts is important in evaluating the hydrology and ecological limits of the lake. The dynamics of the catchment should therefore guide integrated planning and improved policy on natural resources management.

The geological setting within the East African Rift

The tectonic structure of the East African Rift Valley in Kenya has been the subject of many geological studies (e.g. Bosworth, 1987; Khan and Mansfield, 1971; KRISP, 1987; Baker, 1986; Fairhead, 1976). In longitudinal profile, the elevation of the Rift Valley reflects the up-arched shape of the adjacent mountains (Mount Kenya, Aberdare Ranges, Tinderet volcano). Baker, Mohr, and Williams (1972) propose that the subvolcanic surface under the rift floor is deepest where the adjacent plateau is most uplifted. Alkaline volcanism associated with the rifting has infilled the floor with 2–3 km thick pumiceous pyroclastics, ashes, trachytes, ignimbrites, phonolites, and phonolitic trachytes (Baker, 1986). Morley *et al.* (1990) note that the major faults display large-scale structural domains with a consistent structural style, controlled by the geometry of those faults with displacement of more than 1,000 m.

The effective elastic thickness of the crust beneath the East African Rift Valley has been estimated at 21–36 km by Ebinger *et al.* (1989) using seismic data. This points to mechanically weakened topography within the severely faulted rift. Ebinger *et al.* (1989) also point to heating of the lithosphere above a convecting region within the asthenosphere. The active zone along the rift and doming imply upflow zones linked to high-level intrusions (Torfeson, 1987). The Kenya Rift, according to Morgan (1983), is thus characterized by an average heat flow of 100 mW/m^2, indicating an elevated geotherm. Lambiase (1989) and Khan and Mansfield (1971) have interpreted a positive gravity anomaly, which they associate with axial rift volcanism and shallow magma intrusion. Tectonic movement on the main faults probably followed intrusive magma forming the Kenya dome and the volcanic centres on the rift floor axis. These movements show "spoon fault" collapse (Chorowicz, Fournier, and Vidal, 1987) or detachment surfaces that caused a tilt towards the east, on the downthrown blocks.

In cross-profile the faulting is intense at the rift axis, leading to subparallel north-south elongated horst and graben structures. These structures appear as ramps formed by major faults arranged in *en echélon* patterns ("S" forms or sigmoidal shapes – Chorowicz, Fournier, and Vidal, 1987), which portray an oblique lateral movement (Strecker, Blisniuk, and Eisbacher, 1990) due to shearing along the Marmanet-Siracho-Loboi cross-structure. The upthrow and downthrow sides of the faults are connected. McCall (1967) portrays the rift floor fault systems as a series of anatomizing and bifurcating faults with short-segment cross-structures obliquely cutting the main faults.

The morphotectonic structure of the Lake Bogoria area

Three morphotectonic regions (the Elgeyo Detachment, Aberdare Detachment, and Nguruman Detachment) characterize the Kenyan section of the East African Rift Valley (Onywere, 1997; Grimaud *et al.*, 1994). Several structural frameworks – major and minor grid faults, major and minor tilted blocks and rhomb-shaped horsts, fault swarms, and shallow, narrow water bodies – give the detachments a unique tectonic style reflected in the morphology of the land. Spreading or accommodation zones separate the detachments (Chorowicz *et al.*, 1988). The Aberdare Detachment is located in the central part and marked by three general homogeneous areas – the Sattima-Mau Block (N18°W general trend), the Solai-Subukia Block (N11°E), and the Lake Bogoria Block (north-south). Its tectonics is reflected in rhomb-shaped horst structures and relay ramp geometry linked to interference of the fault trends at the accommodation zones.

The Lake Bogoria Block, the subject of this study, is defined by east-dip tilted blocks marked by antithetic grid faults cutting the trachyphonolites of the Lake Hannington series dated by Griffiths and Gibson (1980) at 0.3 Ma. The faults form ribbon-like structures (*en lanières*) truncated to the south by the Menengai caldera volcanism and to the north by a N30°W trending Aswa lineament represented in the area by the Marmanet-Siracho-Loboi cross-structure. Each of the *en lanières* defines narrow horsts (<1 km wide) alternating with similarly narrow grabens infilled with Quaternary to Recent fluvial lacustrine sediments (McCall, 1967).

The Lake Bogoria and Marmanet faults are southern extensions of the Laikipia border fault, a tectonic structure characterized by basalts and phonolites of the Lower Miocene (Baker, Mohr, and Williams, 1972). The basalts underlie the plateau trachytes at the rift floor, and are exposed capping the Laikipia Plateau. As suggested by Baker and Mitchell (1976), the basalts were faulted before at least 1.4–0.8 Ma when the plateau trachytes were emplaced.

Climate and hydrology

The hydrology of the catchment and the dominance by hot springs drive the ecology of Lake Bogoria. Data from meteorological observations at three stations indicate that annual rainfall, from averages taken over a 30-year period (1962–1991) and measured in a standard rain gauge (12.7 cm diameter, set 30 mm above the ground), varies between 645 mm and 980 mm (Perkerra Irrigation Scheme Station, 8935163, 1,067 m, 0° 28′ N, 35° 58′ E, 647.4 mm; Marmanet Forest Station, 8936023, 2,300 m, 0° 06′ N, 36° 18′ E, 930.4 mm; Nyandarua Agricultural Station, 9036135, 2,378 m, 0° 02′ S, 36° 21′ E, 979.2 mm). There is a general decrease of rainfall from the rift shoulder escarpments into the rift floor, and from the highest part of the rift floor at Menengai towards Lake Bogoria.

Annual mean evaporation (2,060 mm, using pan type "A") far exceeds the annual mean precipitation (852 mm), accounting for high losses of moisture. Daily sunshine hours are on average 8.6 hours for most of the area, making it warm and sometimes hot throughout the year. There is a marked hot and dry spell in January–February. The average maximum monthly temperatures (34°C) are higher at Lake Bogoria in these two months than in other months. There is very low rainfall reliability and the area is semi-arid. The upper reaches of the Marmanet escarpment above 2,000 m altitude mark the high-rainfall zone and favour infiltration. Highland deciduous forests and thick bushes mark this area. Data from electrical resistivity surveys indicate that the percolating waters recharge the water table, feeding the springs at the foot of the escarpments. This forested area, when well watered, is therefore an outstanding catchment for water resource development at the foot of the escarpment.

Marmanet Forest Station is within the catchment and its slightly higher rainfall and a cooler climate make the catchment area suitable for rain-fed agriculture. It experiences demographic pressure – mainly peremptory exploitation of the natural resources for agriculture, grazing, sources of construction materials, food, and fuelwood. The impact of these activities on the fragile ecosystem of Lake Bogoria raises critical vulnerability issues related to biodiversity – destruction of wildlife habitat, degradation of water recharge and quality, and retarded forest sector development. Irregular changes in the water volume in response to exceptional climatic conditions affect the chemistry, salinity, productivity, biochemical oxygen demand, and nutrients in the lake. When the water volume drops the level of salinity rises, which reduces the growth of the algae and/or renders it toxic to the flamingoes. This prompts the migration of the flamingoes in search of alternative sources of food. On the other hand dilution of the salinity levels such as it happens during periods of exceptional rainfall prompts the flamingoes also to migrate. Such migration from the lake was recorded for example in 1997 when the El Niño rains diluted the salinity of the water.

The larger part of the surface drainage area (1,075.5 km^2 of watershed) is occupied by the Waseges River, which drains the plateau and the escarpment area through springs and short tributaries. The river flows north-westerly at the foot of the Marmanet escarpment, diverting its course at Chesauilmet fracture zone to flow westward down the Ngusero, Waseges, and Sandai fault scarps, where it has cut the 600 m deep Sandai Gorge. At the foot of the Sandai escarpment the river flows into the Kisibor Swamp, its base level, where it has built a deltaic sediment fan. The drainage from the swamp is controlled by the back tilt of a fault scarp, separating this swamp from the Loboi Swamp. The constructive sediment fan outwash has helped channel the waters into Lake Bogoria.

Image analysis and data modelling

Three full scenes of Landsat TM images (path 169/Raw 060) of January 1986 L5, March 1989 L4, and March 2000 L5 were rectified by convolution interpolation algorithm, trained on ground control points of the 1986 image. The image subsets for the area were localized on Lake Bogoria. These were georeferenced and reprojected to UTM coordinates for integration with georeferenced GIS vector datasets consisting of lithology, drainage, structures, and elevation. A technique of information extraction and representation based on the application of statistical algorithms using the image-processing software ERDAS Imagine was then followed (ERDAS Imagine Tour Field Guide, 2001). Firstly, covariance matrix evaluation showed that bands 1, 2, and 3 were correlated. These bands are in the spectral region where reflectance curves of natural materials are relatively smooth. A sum average of bands 1 and 2 (green) was made to reduce on the redundancy in the data. The new band was subset with bands 3 (red) and 4 (infrared) for the analysis.

Downfaulting to the west, sun elevation of 53°, sun azimuth of 102°, and the near north-south trend of the faults result in their enhancement on the satellite imagery. Sharp boundaries border the horsts, enhanced by the graben structures showing on false colour composite (FCC) imagery as white reflectance. Interpretation made from satellite imagery and existing geological map overlays containing structural and drainage coverages suggests rift offsets in the area. These are marked by shorter, near east-west trending faults observed on directionally filtered and edge-enhanced satellite imagery. The Lake Bogoria scene is characterized by a strong variance (water, thick deciduous bush, bare ground of horst/graben, silted graben surface, marsh reed swamps) used as mapping units in the land-cover classification. The image view of the area shows submeridian striking lineaments of fault scarps and associated grabens and horsts.

Pattern recognition techniques based on mathematical probabilities were applied to build classification models for discriminating the land cover. Ilyin *et al.* (1983) show that the reflectance characteristic of materials is a consequence of the chemistry and physics of the material modified by environmental factors and physical conditions. The theory behind interpretation of land cover lies in the spectral properties of reflecting objects and their morphological disposition. Kartikeyan, Majumder, and Dasgupta (1995) point out that, although digital methods are fast and accurate when the model assumptions are true, their success is limited by natural variability of the landscape and oversimplicity of the model assumptions. Different land-use categories have different probability models, and the spectral signature of a class varies dynamically and from image to image. In analysing remote-sensing data for land-cover classification, three main issues are of importance: models that represents signature extraction; quantification of different classes from image signatures; and use of geographic and geometric information in a GIS database for visualization.

The wavelength range of Lake Bogoria image data specified a high degree of reflectance contrast of the study area parameters. Topographic variations and vegetal cover, influenced by drainage, dictate the parameters. The drainage density and patterns in Lake Bogoria reflect low density at the horst/graben structures of the Kipngatip Plateau and a higher density on the major escarpments. Indirect influence on drainage reveals the control of geology and the influence of climate. There is a higher density of drainage in the wetter Marmanet escarpment. Spatial and spectral enhancements of the data revealed details of the nature of the land, providing opportunities to study variation in geology and agricultural practices in the area. Land-cover classes were extracted and coded for determination of the 12 land-cover categories, which compared favourably with a combined NDVI image. The following land-cover classes were interpreted:

- Marmanet forest area, marked by forest and three types of agricultural field covers
- the horst structures and the escarpment faces, marked by scattered grass and scattered bushes; thick grassland with scattered bushes
- Lake Bogoria, marked by the lake; lakeshore silts and deltaic deposits; open soils and shore deposits
- sediment traps of the graben depressions and low sediment accumulational landforms consisting of graben grassland; valley-bottom vegetation and bushland

- Loboi/Kisibor Swamps, marked by swamp vegetation and high-chlorophyll vegetation.

The changes detected between 1986–1989, 1986–2000, and 1989–2000, using TM band 4 (infrared), band 3 (red), and bands 1 and 2 combined (green), reveal changes in land use since 1986. These changes are congruent with socio-economic forces operating in the area (population growth, social structures and values, changes in the economy) all exerting new demands on the land. A combination of three NDVI images, 1986 (green), 1989 (red), and 2000 (blue), shows vegetation concentrations on the NDVI indexed image. In terms of vegetal cover the areas showing up in white hues had no change since 1986. Circular features, also showing up in white hues, mark points of water concentration and emerging springs at the foot of the escarpment. These are areas of dense vegetation mapped as well-developed groves of fig and acacia-ficus trees.

The impacted areas, mainly in Marmanet forest and the swamps area, show up in yellow and blue hues. Variations in floristic composition of the phreatophytic vegetation in the swamps recorded by the NDVI image imply variations in the nutrient composition and silt impacts. Lake Bogoria was in particular infested with plumes of phreatophytic vegetation – a contribution from the 1989 image. The plumes are absent in both the 1986 and 2000 images, implying a temporal impact during the 1989 period. Such variations can be used to monitor the impacts on the flamingo population.

Using grid-based GIS, it was possible to compute an optimal corridor of erosion using grid drainage data and grid cell overlays of weighted classification of land cover, slope, and geology. This resulted in a numeric surface of composite data expressing erosion hazard in the area. Most of the area has high erosion hazard, and it is apparent that agriculture has degraded the Marmanet plateau and increased erosion in that area. The major escarpments are also depicted as prone to landslides. A buffer-zone conservation action plan approach to forest resource conservation in the Marmanet area is needed to mitigate this impact.

The surface roughness of the area evaluated from the difference between the 2D planimetric surface area (730.69 km^2) and the 3D surface model (759.4 km^2) gave a volume of material of 368.28 km^2. Thus an average thickness is 504 m above the 1,000 m surface above sea level. The border faults have, however, throws exceeding 600 m and have over the geological period been affected by tectonic collapse, leading to tilting towards the east. These fairly high topographic differences point to vulnerability of the land to soil erosion. The influence of geology and land cover point to areas that are suitable for cultivated agriculture. It is inferred from the spatial data modelling and temporal models that the Marmanet escarpment area and the Lake Bogoria escarpment have slope characteristics (slope angles $> 10°$, with the upper slopes $> 30°$). These slopes make them naturally prone to slope instability and determine their suitability for a particular land use. The footslope landforms imply that mass movement has been prevalent in the landscape sculpturing.

Surface modelling and data interpretation

The use of ArcView/ArcGIS and the visualization capability of ArcView 3D Analysti allowed for analysis and visualization of terrain elevation data and integration of image data, image classification results, and non-spectral knowledge vector GIS data in the 3D scene. The interactive environment allowed manipulation of the data and cartographic information, leading to geographic visualization and creation of a virtual environment for slope evaluation and the study of trends in the morphology and land use. The selection of appropriate symbolization drastically changed the appearance of the map and made it easier to interpret the data. The factors dealt with included geographic shape, surface relief, texture, subset data analysis, classification of data, attribute display, and map scale. Some of the surface analysis functions used TIN and GRID models of elevation data gridded at 100 m intervals to create slope models. The TIN model was used as a surface to drape image data and the vector datasets. This revealed the structure of the terrain and the lines of surface runoff. The erosion hazard map was especially valuable in evaluating the effect of land use in the Lake Bogoria area.

Morpho-structural interpretation of the image of Lake Bogoria on the digital elevation model reveals subparallel linear fault patterns and narrow tilted blocks with a weak easterly dip. Strike or relay ramp patterns characterize it. The ramps occur because each linear structure dies out laterally to the north and south and is picked up by other linear features. These ramps serve to collect drainage and channel it northward. The drainage from Kisanana-Chemasa-Emsoss, Chui-Maryland-Lolderodo, Solai, Subukia, and Marmanet escarpments collect along the ramps and flow northerly mainly through the Waseges into Lake Bogoria.

From the image model and the vector data, a likely area where groundwater may concentrate was judged from the density of fault structures and the type of rock. The morphology of the drainage basin was delineated by considering the texture of the drainage divides, the density of the drainage channels, and the path taken by the drainage over the fault structures. A high density of short drainage features marked short fractures on the faces of the larger escarpments. These were enhanced by riparian and phreatophyte vegetation. The alluvial fans and marsh at the Loboi and Kisibor plains influence the movement and accumulation of surface and subsurface waters. The plains, at an elevation of 1,020 m, are a consequence of thick alluvial deposits over the geological period. The sediment load has been brought in by the Molo, Waseges, and Perkerra Rivers, which together flood the Loboi, Kisibor, and Ngarua plains. Some silt, over which some irrigation is taking place, has been transported by the Molo River from as far south as Molo. The sediment deposits include reworked and redeposited pyroclastics, volcanic "sands", gravel, pebbles, and even boulders washed in from the neighbouring cliffs. Most of these lacustrine deposits have concealed the fault structures. The presence of the sediments gives the possibility of a high potential for groundwater storage. This plain area is characterized by swamp vegetation.

Despite the presence of relatively thick sediments at the plains, however, there is a total lack of similar sediments in Lake Bogoria itself. The lake has a very poor supply of lacustrine sediments, in response to both the small drainage area and very low rainfall; also the fact that no major river takes its waters directly into the lake largely contributes to the lack of sediments in the lake. The Waseges, which would have supplied the main sediment load, silts into the Kisibor Swamp and only feeds the lake through an overflow channel, thus reducing the impacts of the silts before its water reaches the lake. The role of the swamps in containing the nutrient movement needs chemical sampling and testing. The current policy of water extraction for irrigation at the Perkerra irrigation scheme to the north should also be discouraged, as this increases erosion hazard.

The area traversed by the Waseges and its tributaries is a steep-step faulted terrain. Under current land-use practices (felling of trees and clearing of land for agriculture) the area is prone to soil erosion, frequent mudslides and landslides, and lake-water pollution through agricultural wash-off. The slope demolition process through mass movement and exposure of the surface to fluvial incision also leads to riverbank erosion, expansion of stream channels, and removal of vegetation along the watercourse accelerated by the slope conditions and the land tilt from the Bahati/Menengai fracture zone. Research done by Westerberg and Christiansson (1998) on slope instability in the Nyandarua area (Aberdare Highlands) to the south-east of the study area indicates that slope instability in the area is a consequence of the interrelation between land use and the natural causal factors such as climatic conditions, in particular high rainfall events, slope characteristics, and soil type. In the Marmanet area, translational slides occur in steep slope positions where the depth of the overburden has the same thickness as that of the root zone. These slides are triggered by rapid saturation of the soil, which reduces cohesion, surface tension, and friction.

The nature of faulting along the length of the Chui-Maryland-Lolderodo and Marmanet faults portrays "spoon-shaped" structures due to a tectonic slip on their concave side, similar to a large-scale landslide. The spoon-shaped structures control the morphotectonic evolution of the escarpment, the foot of which reflects scree deposits derived from landslides. Some of the landslides are attributed to large earthquake movements that occasionally occur at the rift (Girdler *et al.*, 1969). These earthquakes also led to open-fault gushes reported by McCall (1967) as lying below the Marmanet fault at Subukia. Such open-fault gushes have also been reported at the Kedong Valley south of the area (Onywere, 1997), and are the escape route for the rivers crossing them.

There is marked low density of drainage on the south-western parts, explained by the disappearance of the drainage features at open-fault gushes. The surface runoff percolates through these gushes and serves as recharge to the underlying water table and the geothermal reservoirs. This is the source of water for the hot springs that emerge around the lake from the south.

Summary

Incorporation of remote-sensing data into a GIS database allowed use of ancillary data that improved mapping accuracy and modelling. This also provided cartographic ability that addressed questions such as the inter-relationship between morphology and land-use patterns. Vector GIS data have the potential to be integrated with satellite raster GIS data through image processing, as the datasets possess spatial reference. The implication of land-use trends and practices mapped from Landsat TM satellite data is made apparent when topographic information in DEM form is integrated. The erosion hazard model stresses the importance of morphotectonic control over the drainage and other surface processes such as landslides that have led to scree deposits and fan delta deposits at the foot of the escarpments.

Satellite data have been used to update the vector database and have high prospects in the analysis of drainage patterns and change detection. The data have also been used in the detection of geomorphic landscape units and land-use patterns in the Lake Bogoria area, managed through the database. At present the utilization of this potential and participation and experimentation with remote-sensing data are minimal in the country. To facilitate and accommodate continual building, analysis, and dissemination of regional GIS information, there is a need to incorporate accurate updates of the various spatial data entities and to participate in the use of the data as a resource conservation strategy. This can be used to address the more important question of environmental degradation.

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REFERENCES

Baker, B. H. 1986. *Tectonics in the Southern Kenya Rift Valley and its Influence on Rift Sedimentation, Sedimentation in the Eastern Africa Rifts*, Special Publication 25. London: Geological Society, pp. 45–57.

Baker, B. H and J. G. Mitchell. 1976. ''Volcanic stratigraphy and geochronology of the Kedong-Olorgesailie area and the evolution of the south Kenya Rift Valley'', *Journal of the Geological Society of London*, Vol. 132, pp. 467–484.

Baker, B. H., P. A. Mohr, and L. A. J. Williams. 1972. *Geology of the Eastern Rift System of Africa*, Special Paper 136. Geological Society of America, pp. 1–67.

BBC. Undated. www.bbc.co.uk/nature/animals/news/125news2.shtml.

Bosworth, W. 1987. ''Off-axis volcanism in the Gregory Rift, East Africa: Implications for models of continental rifting'', *Geology*, Vol. 15, pp. 397–400.

Chorowicz, J., J. L. Fournier, and G. Vidal. 1987. ''A model for rift development in East Africa'', *Geological Journal*, Vol. 22, pp. 495–513.

Chorowicz, J., M. Guezlane, J. P. Rudant, and G. Vidal. 1988. ''Analysis of the Aswa fault zone in Kenya from Landsat MSS and MOMS-01 space imagery: Influence of Precambrian heritage on the Gregory Rift structures'', *Comptes rendus de l'Académie des Sciences, Paris*, Vol. 307, Series II, pp. 83–88.

Clarke, M. C. G., D. G. Woodhall, D. Allen, and W. G. Darling. 1990. *Geological, Volcanological and Hydrological Controls on the Occurrence of Geothermal Activity in the Area Surrounding Lake Naivasha, Kenya*. Nairobi: Ministry of Energy, p. 138.

Ebinger, C. J., T. D. Bechtel, D. W. Forsyth, and C. O. Bowin. 1989. ''Effective elastic thickness beneath the East African and Afar plateaus and the dynamics of the uplifts'', *Journal of Geophysical Research*, Vol. 94, No. B3, pp. 2883–2901.

ERDAS Imagine Tour Field Guide. 2001. National Centre for Geographic Information and Analysis, Version 8.5. Atlanta: ERDAS.

Fairhead, J. 1976. "Structure of the lithosphere beneath the Eastern Rift, East Africa, deduced from gravity studies", *Journal of Tectonophysics*, Vol. 30, pp. 269–298.

Gathaara, G. N. 1999. *Aerial Survey of the Destruction of Mt Kenya, Imenti and Engare Ndare Forests*, Forest Conservation Programme Report. Nairobi: Kenya Wildlife Services.

Girdler, R. W., J. D. Fairhead, R. C. Searle, and W. T. C. Sowerbutts. 1969. "Evolution of rifting in Africa", *Nature*, Vol. 224, pp. 1178–1182.

Griffiths, P. S. and I. L. Gibson. 1980. "The geology and petrology of the Hannington trachyphonolite formation, Kenya Rift Valley", *Lithos*, Vol. 13, pp. 43–53.

Grimaud, P., J. P. Richert, J. Rolet, J. J. Teircelin, J. P. Xavier, C. K. Morley, C. Coussement, S. W. Karanja, R. W. Renaut, G. Guern, C. le Turdu, and G. Michel-Noel. 1994. "Fault geometry and extension mechanisms in the Central Kenya Rift Valley, East Africa. A 3D remote sensing approach", *Bulletin des Centres de Recherches, Explo.-Prod. Elf-Aquitaine*, Vol. 18, No. 1, pp. 59–92.

Ilyin, A. V., M. Z. Glukhovsky, V. V. Koslov, M. V. Moralev, and A. L. Startzev. 1983. "The application of space imagery to geology and mineral exploration in the USSR – A case history", *Advances in Space Research*, Vol. 3, No. 2, pp. 19–26.

Kartikeyan, B., K. L. Majumder, and A. R. Dasgupta. 1995. "An expert system for land cover classification", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 33, No. 1, pp. 58–66.

Kenya Wildlife Service. Undated. www.kenya-wildlife-service.org/death-fl.htm.

Khan, M. A. and J. Mansfield. 1971. "Gravity measurements in the Gregory Rift", *Nature (London), Physical Science*, Vol. 229, pp. 72–75.

KRISP Working Group. 1987. "Kenya Rift International Scientific Project: Preliminary results", *Nature*, Vol. 325, pp. 239–242.

Lambiase, J. J. 1989. "The framework of African rifting during the Phanerozoic", *Journal of African Earth Sciences*, Vol. 8, Nos 2/3/4, pp. 183–190.

McCall, G. J. H. 1967. *Geology of the Nakuru-Thomson's Falls-Lake Hannington Area*, Report No. 78. Nairobi: Geological Survey of Kenya, p. 122.

Morgan, P. 1983. "Constraints on rift thermal processes from heat flow and uplift", *Tectophysics*, Vol. 94, pp. 277–298.

Morley, C. K., R. A. Nelson, T. L. Patton, and S. G. Munn. 1990. "Transfer zones in the East African Rift system and their relevance to hydrocarbons exploration in rifts", *American Association of Petroleum Geologists Bulletin*, Vol. 74, No. 8, pp. 1234–1253.

Onywere, S. M. 1997. "Structural analysis of the drainage basin of Kenyan Rift Valley lakes within the Aberdare Detachment using satellite data, GIS and field observations", unpublished PhD thesis, Department of Geology, University of Nairobi, p. 200.

Onywere, S. M., N. K. Opiyo, S. J. Gaciri, and M. J. de Wit. 2000. "A methodology for image analysis and land cover classification of Nakuru-Menengai area

(Central Rift Valley, Kenya)'', *African Journal of Science and Technology*, Vol. 1, No. 1, pp. 56–67.

Strecker, M. R., P. M. Blisniuk, and G. H. Eisbacher. 1990. ''Rotation of extension direction in the central Kenya Rift'', *Geology*, Vol. 18, pp. 299–302.

Torfeson, H. 1987. ''Geothermal and geological survey of Mt Suswa'', unpublished Technical Report KEN/82/002. Nairobi: UNDP/DTCD, p. 64.

Westerberg, L. O. and C. Christiansson. 1998. ''Landslides in East African highlands: Slope instability and its interrelationship with landscape characteristics and land use'', *Advances in GeoEcology*, Vol. 31, pp. 317–325.

14

A catchment model of runoff and sediment yield for semi-arid areas

Joy Apiyo Obando

Introduction

Models can be used to enhance understanding of dynamic processes which are difficult to observe in nature. Furthermore, models can be used to predict the rates of processes under different conditions, and thereby provide tools for planning land use. In particular, arid and semi-arid lands (ASALs) are susceptible to land-use changes due to increasing human settlements, yet estimating erosion rates is difficult because of the infrequent rainfall events. The development of ASALs in Kenya is therefore considered crucial, since about 35 per cent of the population and 50 per cent of the livestock are found in these areas (Langat and Mwangata, 1994). In order to utilize these areas sustainably, it is necessary for proper planning to be undertaken with the aim of long-term sustained agricultural productivity. It is only under such conditions that the government's goal of food security stipulated in its development plans (1997–2001, 2002–2006) will be achieved (Government of Kenya, 1997, 2002).

Objective

The objective of the research is to develop a model that can be used in semi-arid catchments to:

- understand the dynamic interactions between soil moisture, vegetation, and rainfall
- simulate runoff and sediment yield
- plan land use.

Methodology

The model (SEM) is designed to simulate the hydrologic behaviour of the soil and to estimate the sediment yield of the catchment, with regenerating vegetation. The overall behaviour of the interactions is developed by a series of submodels, namely the hydrology, plant growth, runoff, and sediment yield. The programme listing, written in QuickBasic language, together with relevant explanations are given in Obando (1996).

Model development

Figure 14.1 shows the submodels and interactions among the variables.

Model structure

The basis of the soil moisture is described as a simple water-balance equation (equation 1):

$$S_t = S_0 + P - E - Q - Q_d \tag{1}$$

where all the units are in mm/day; S_t is the current moisture content of the soil and S_0 is the previous moisture; P is the daily rainfall amount and forms the main input; E is the evapotranspiration (this includes the bare soil evaporation, E_s, and plant transpiration that is assumed to be equal to the actual evapotranspiration, E_t; it also includes the interception loss); Q is the total runoff, which is the sum of the Hortonian and saturation overland flow (H_{of} and S_{of}); and Q_d is the drainage beyond the rooting zone. See Figure 14.2 for the conceptual store of the model.

Although the units of equation 1 are given in mm/day, thereby indicating an overall daily soil moisture budget, the specific processes within the model are computed for hourly time steps for given rainfall events.

In the hydrology component, the infiltration and storage models are combined to generate both Hortonian and saturated overland flow respectively (Figure 14.2). The plant growth is computed as the accumulation of dry-matter biomass using water-use efficiency and evapotranspiration. The vegetation therefore interacts dynamically with the soil moisture regime through the actual evapotranspiration, and hence con-

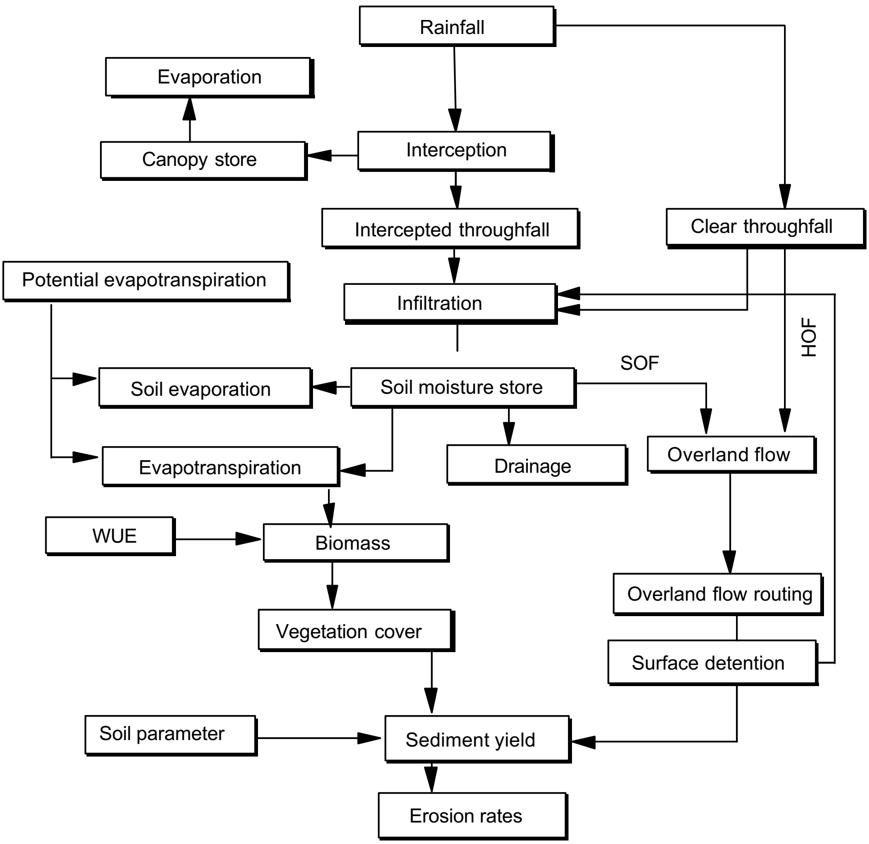

Figure 14.1 Flow chart of the model

trols the possibility of runoff generation and production of sediment yield. For details on the plant growth model see Obando (1996); this chapter discusses only generation of runoff and sediment yield.

Generation of runoff and sediment yield

In the model developed here, surface runoff is generated either as Hortonian overland flow, which occurs when the rainfall intensity exceeds the infiltration rate, or as saturation overland flow. The generated runoff is routed within the catchment using a single-direction routing algorithm, together with a Strahler network-ordering scheme to sequence the flow. This approach requires a regular gridded digital elevation model of the catchment and considers the elevation of each cell relative to its sur-

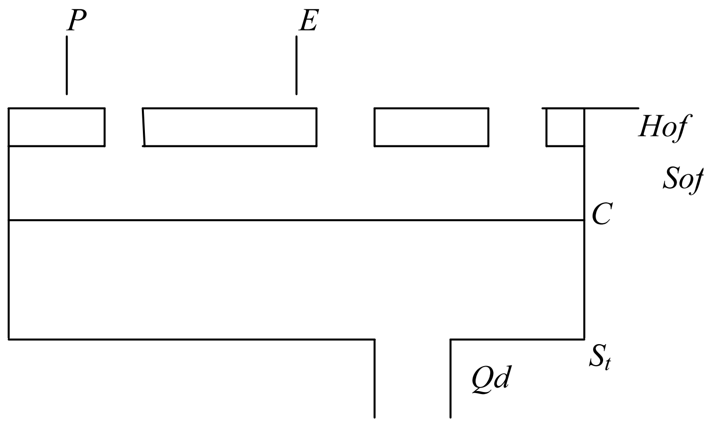

Figure 14.2 Conceptual soil moisture store for the hydrology model

rounding neighbours. The flow is routed by transferring the overland flow along a pre-defined network of pathways until the channel mouth is reached. The velocity of the flow and the resultant discharge are determined for each cell on the basis of the stream network.

A regular gridded digital elevation model (DEM) of a subcatchment (Figure 14.3) has been used in simulating a network of flowpaths along which the overland flow is then routed. The Strahler network-ordering scheme has been used to identify the flowpaths for the overland flow routing. Using the neighbourhood method, the maximum gradient is selected so as to determine the direction of flow. The joining of two first-order streams creates a second-order stream, and so on. These paths are then stored as the network map and used in the routing of the generated overland flow.

In routing the overland flow, the approach adopted here recognizes the importance of topography (gradient and geometry). Several hydrological models have used DEMs for overland flow routing (O'Loughlin, 1981, 1986; Moore *et al.*, 1986; Quinn *et al.*, 1993). The single-flow direction algorithm for eight neighbouring cells is used here for routing overland flow. Figure 14.4 illustrates the resultant effects of this weighting such that the largest amount of discharge is transferred in the direction of the steepest gradient; the thickness of arrow is proportional to the amount of flow in this example, such that S1, S2, and S3, which have slope gradients of 10°, 35°, and 2° of slope, receive 20 per cent, 70 per cent, and 1 per cent of the discharge respectively. The remaining overland flow is distributed in the surrounding cells in proportion to the gradient, thereby diffusing the flow. This method allows routing across the grids from the source

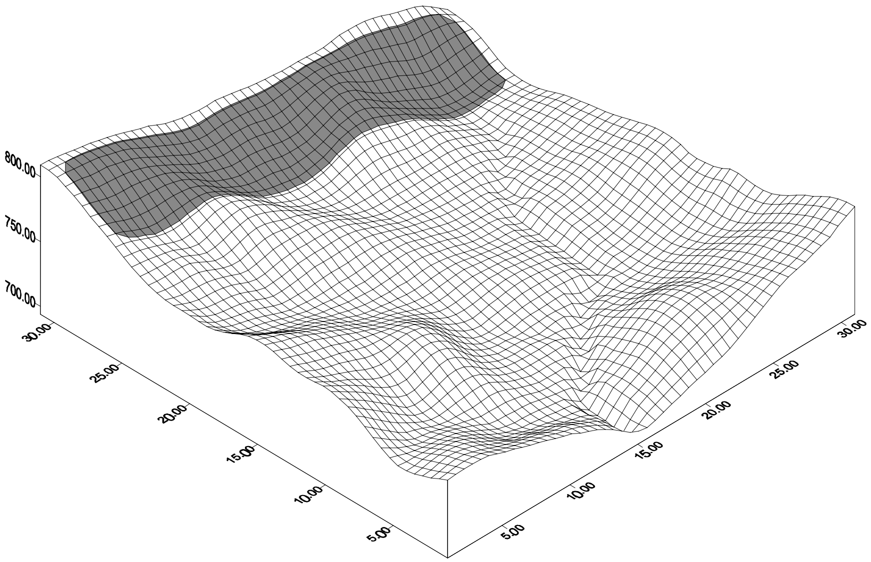

Figure 14.3 A regular gridded digital elevation model of the subcatchment

cell to those of a lower elevation along the ordered network until the flow terminates in the channel mouth, where the elevation is lowest. The overland flow generated in the model is routed on an event basis at the end of the storm and is assumed to occur in one hour. The discharge is calculated as a function of the surface roughness, depth of flow, and velocity.

The erosion rate (E) is obtained by including the effects of soil structure, slope, and vegetation cover. The expression (equation 2) combines

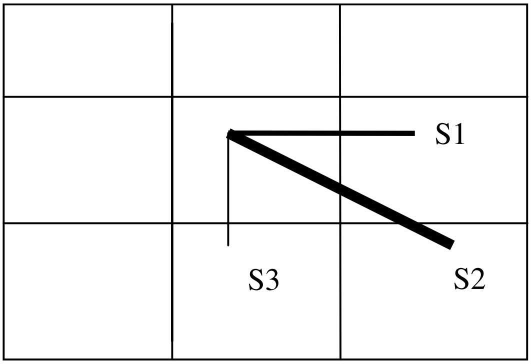

Figure 14.4 Diffusing the flow to neighbouring cells

the power function for overland flow and slope, and an exponential reduction of erosion due to vegetation cover:

$$E = Kq^m S^n e^{-bVc} \tag{2}$$

where K (dimensionless) is a soil parameter which describes the erodibility of the soil; q is the discharge (m^3/s); S is $\tan\beta$ where β is the slope in degrees; V_c is the percentage of vegetation cover; E is the erosion (mm/m); and b, m, and n are dimensionless parameters – b relates to the reduction in erosion due to vegetation cover, and a value of 0.05 has been used here.

Equation 2 accounts for the hydraulic effects of vegetation. Elwell and Stocking (1976) found an exponential relationship between the mean annual soil loss and runoff, and vegetal cover on grazing land in Zimbabwe. Dunne, Dietrich, and Brunengo (1978), Moore, Thomas, and Barber (1979), and Francis and Thornes (1990) have obtained similar results.

The sediment yield is then estimated using this outflow together with the slope gradient, soil factor, and the corresponding vegetation cover characteristics, which vary spatially and temporally due to different patterns and percentages of vegetation cover. The sediment yield in the cells is then summed daily and annually to provide the values for the catchment. Daily and annual estimates of the overland flow, sediment yield, and erosion rates are calculated for the catchment under different scenarios. The sediment yield from each cell on days when overland flow is generated provides a sum that can be compared with values for various patterns and percentages of vegetation cover.

Model results

The runoff and sediment yield in the catchment have been evaluated using several model options and input variables in the Rambla del Chortal subcatchment. A regular gridded 20 m resolution DEM of a sub-basin of Rambla del Chortal (Figure 14.3) has been used as the input catchment, covering 0.34 km^2. A bare catchment with 0 per cent cover and a catchment with vegetation cover of 38 per cent are used as control simulations. The Lorca daily rainfall series has been used as input. Other model inputs and outputs are indicated in Table 14.1.

Both field measurements and model data yield an average cover of 38 per cent for this catchment, which represents complete *matorral* shrubland in the Rambla del Chortal area. The catchment with fixed biomass, representing the bare and shrub-covered catchment at a steady state used as control cases, provides the worst- and best-case scenarios for the selected rainfall respectively.

Table 14.1 Model inputs and outputs

Model inputs	Model outputs
Daily rainfall (mm)	
Potential monthly evapotranspiration (mm)	Biomass (g/m^2)
	Vegetation cover (%)
Digital elevation model (x, y coordinates, z height (m))	Litter (g/m^2)
Day length (hours)	
Storm length (hours)	
Ksat (mm/hr)	Soil moisture storage (mm)
Soil moisture capacity (mm)	Evapotranspiration (mm)
Initial soil moisture (mm)	Bare soil evaporation (mm)
Infiltration parameters A (mm/hr), B (mm)	Drainage beyond rooting zone (mm)
Interception storage (mm)	
Water-use efficiency (g DM per kg H_2O)	
Initial biomass (g/m^2) (vegetation %)	
Ratio of above-ground/below-ground biomass (dimensionless)	Overland flow (mm)
	Detention storage (mm)
Respiration coefficient (g DM/day)	Sediment yield (g/m^2)
Manning's n (dimensionless)	Erosion rates (mm/m^2)
Soil parameter *K* (dimensionless)	

Typical simulated results

Figure 14.5 shows the typical daily soil moisture varying with rainfall over a one-year period. The infiltration rate also varies with rainfall amount, as shown in Figure 14.6. For different rainfall series, the soil moisture also varies to reflect changes in rainfall amount over the one-year period, as indicated in Figure 14.7.

A summary of outputs is indicated over a seven-year period (Table 14.2). The dry series records the lowest number of raindays, as is expected, as well as the lowest mean rain per rainday of 5.1 mm compared to 6.0 mm and 6.7 mm for the normal and wet series respectively. Likewise the number of storms greater than 10 mm are lowest for the dry series over this period, with the maximum event being highest for the wet series. Thirty-five per cent, 44.2 per cent, and 23.4 per cent of total rainfall in the first seven years fell in the normal, wet, and dry series respectively. The normal series has a larger number of events greater than 50 mm than either the wet or dry series.

Runoff generation

The annual overland flow generated by the model decreases with increasing vegetation cover in the catchment, illustrating the effect of vegetation

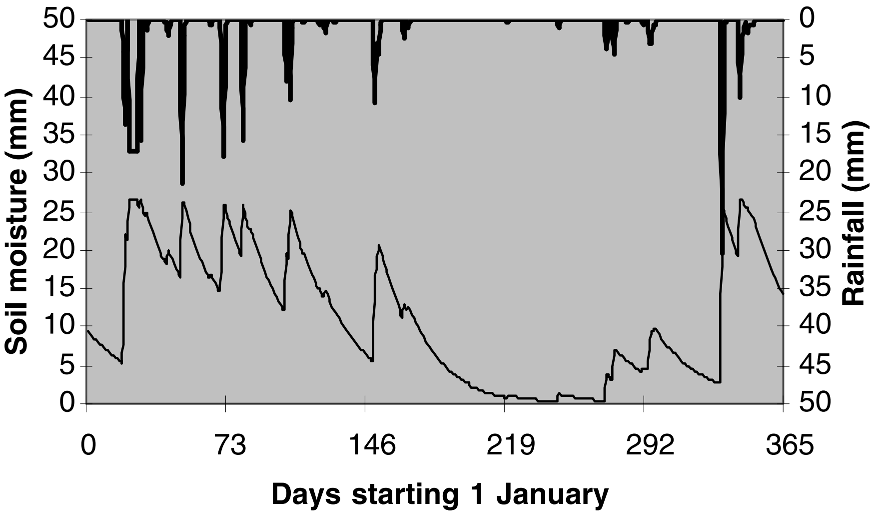

Figure 14.5 Typical daily soil moisture varying with rainfall

cover. Clearly the effect of the regenerating vegetation cover is to reduce the overland flow from the catchment through the influence of the soil moisture budget hydrologically.

The intensity, antecedent moisture, and vegetation cover control the runoff generated. This is illustrated by the runoff coefficients of 38.8 per cent and 26.4 per cent for a bare catchment and a 100 per cent abandoned catchment, respectively (Table 14.3). The effect of vegetation

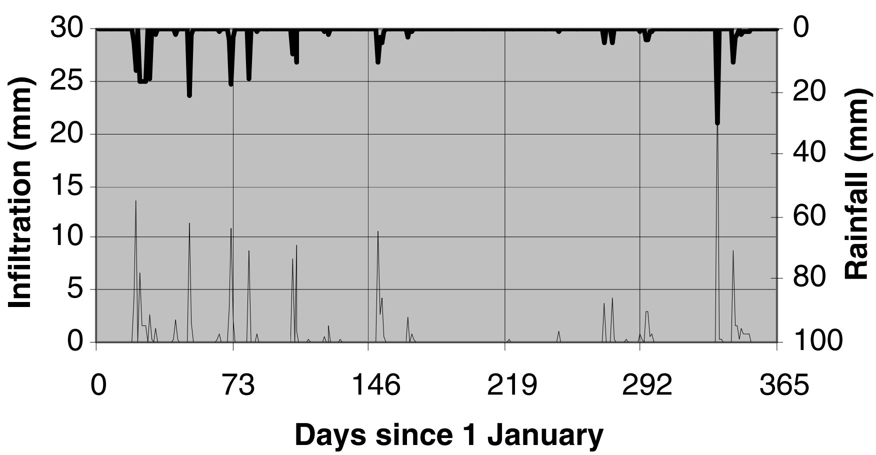

Figure 14.6 Infiltration rate varying with rainfall amount

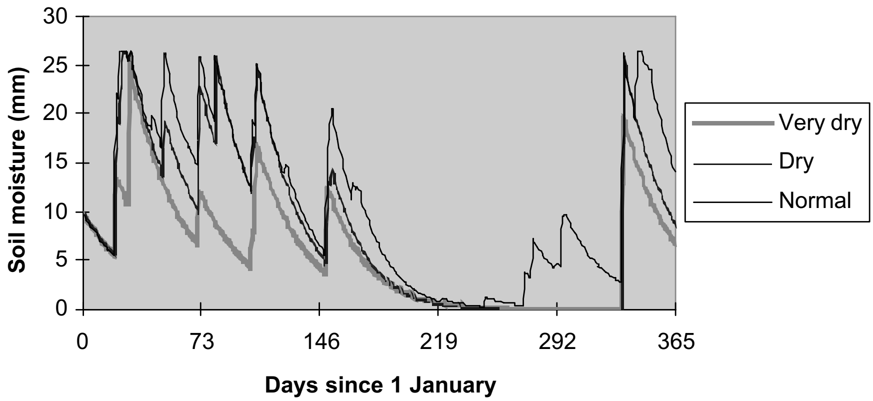

Figure 14.7 Soil moisture simulated using three series of data

Table 14.2 Summary statistics for rainfall in first seven years

Values in mm	Normal series	Wet series	Dry series
Mean	234.6	318.8	138.2
Minimum	95.8	242.6	25.0
Maximum	372.1	359.1	236.6
Standard deviation	81.5	45.9	73.6
Sum	1,641.9	2,231.3	967.3
Maximum daily	86.4	90.0	46.0
Mean rain per rainday	6.0	6.7	5.1
Raindays >10 mm	47	62	26
Raindays >30 mm	6	11	2
Raindays >50 mm	4	2	0
Number of raindays	274	332	188

Table 14.3 Annual runoff simulated from the bare and shrub-covered catchments using different rainfall series

Values in mm	Annual rain (mm)	Annual runoff (mm)		Runoff coefficient %	
		Abandoned	Bare	Abandoned	Bare
Mean	291.7	93.6	132.1	26.4	38.8
Standard Deviation	125.5	83.2	100.7	16.4	17.9
Minimum	25	0	0	0	0
Maximum	651.5	373.7	442.6	61.5	73.9

cover in reducing the runoff generated is more pronounced for low rainfall events. This result also confirms that high-intensity storms are always destructive, even if the catchment has a shrub cover. Secondly, the effect of increasing rainfall is to increase the runoff. A higher proportion of the rainfall ends up as overland flow for the bare catchment than for the 100 per cent abandoned catchment. The abandoned catchment is one which has been left to revegetate naturally with the rainfall.

Sediment yield production

The sediment yield simulated by the model is strongly influenced by the rainfall amount, with higher sediment yield produced from the bare catchment compared to the 100 per cent abandoned catchment. The absolute values of sediment yield from the catchment vary according to the rainfall characteristics, amount of vegetation cover, and slope characteristics. As expected, the bare catchment produces the highest sediment yield for any given rainfall amount. The mean reduction in erosion due to 38 per cent cover (on the 100 per cent abandoned catchment) is nine times, and varies between seven and 350. The rates of sediment yield on the bare and shrub-covered catchment are in the ranges 7–60 kg/m^2/year and 0.8–8 kg/m^2/year respectively.

These values of sediment yield are consistent with those from field measurements, as shown in Table 14.4. The field values range from 0.02 to 1.4. The model values represent 140 years of rainfall data, compared to the field measures, which are either one-off measurements or for a period of up to four years. From experiments over a period of four years in

Table 14.4 Rates of sediment yield from other field measurements in Spain

Sediment yield rates kg/m^2/year	Method and area	Source
0.02 mean 0.12–0.76	Spain four-year experiments, El Ardal field measurements, high *matorral*, slope 22°	Lopéz-Bermudez *et al.* (1996)
0.102	Field measurements (three years), Spain, on 22 per cent cover	Francis (1990)
0.25	Spain, 34 per cent cover, marl hillslopes	Romero-Diaz *et al.* (1988)
0.2–1.4	Spain, reservoir sedimentation	Lopéz-Bermudez and Gutierrez-Escudero (1982)
0.1–0.9	Spanish Pyrenees, experimental plots on abandoned fields	Garcia-Ruiz *et al.* (1995)

El Ardal field sites in Spain, Lopéz-Bermudez *et al.* (1996) obtained very variable soil losses with a low average value of 0.02 kg/m^2. On slopes covered with natural *matorral* the soil losses are lower, with an average value of 0.012 kg/m^2 in spite of a slope gradient of 22°. The values are very variable even on the natural *matorral*, reaching as high as 0.076 kg/m^2. Individual plots under different treatments including wheat and barley cultivation produced more losses, with a mean of 0.1 kg/m^2.

The erosion rates simulated by the model on the 100 per cent abandoned catchment are slightly higher than those measured from plots of abandoned land in Murcia. Using erosion plots on fallow land, Francis (1990) measured rates of soil loss of 0.102 kg/m^2/year between 1986 and 1988 for an average vegetation cover of 22 per cent. The values of soil loss from the model relate to a vegetation of 34 per cent covering the whole catchment. Romero-Diaz *et al.* (1988) reported values of 0.25 kg/m^2/year on marl hillslopes in Murcia. Lopéz-Bermudez and Gutierrez-Escudero (1982) estimate values of soil loss of 0.2–1.4 kg/m^2/year using rates of reservoir sedimentation. Garcia Ruiz *et al.* (1994, 1995) measured runoff coefficients of 20 per cent and sediment yield of 0.9 kg/m^2/year from abandoned fields with 40 per cent shrub cover. Their value lies within the range of the modelled values, with mean sediment yield of 0.8 kg/m^2/year.

The mean value for the rates from the *matorral* catchment is within the permissible soil loss rates estimated by several researchers. The maximum permissible soil loss is the value recommended as the maximum rate of soil erosion that permits a high level of productivity to be sustained in a deep, medium-textured, moderately permeable soil that has subsoil characteristics favourable for plant growth (Mitchell and Bubenzer, 1980). Kirkby (1980) suggests that in current soil conservation practices it is normal to consider rates of erosion of 5–25 tonnes/ha/year (500–2,500 g/m^2/year) as acceptable. This is equivalent to a loss of about 0.2–1 mm/year from the surface (water erosion rates of many undisturbed semi-arid areas are equivalent to 1 mm/year). The value suggested by Mitchell and Bubenzer (1980) of 1.1 kg/m^2/year (1,100 g/m^2/year) falls within this range. Hudson (1995) gives mean annual soil loss varying according to soil type between 0.5 and 1.1 kg/m^2/year as acceptable in the USA. Dunne, Dietrich, and Brunengo (1978) have estimated rates in Kenya to range from 0.01 to 0.02 mm/year in the humid areas, but to fall below 0.01 mm/year in the semi-arid areas. Naturally occurring steep slopes will be more vulnerable and hence the acceptable rates of soil erosion may be higher. The rates of erosion quantified using USLE for the Guadalentin basin in south-east Spain are much higher than this. Soil losses greater that 5 kg/m^2/year are estimated in marginal agricultural fields with slopes > 12 per cent or in areas with sparse scrubland slope > 25 per cent. It must be remembered that the use of the USLE always overestimates erosion.

Conclusions

The runoff generation and sediment yield in the semi-arid catchment depend to a large extent on the rainfall characteristics, topography, and vegetation cover. Generally, increasing rainfall will lead to a corresponding increase in vegetation cover percentage and thus a reduction in the runoff and sediment yield. However, high-intensity storms tend to produce high runoff rates and sediment yield irrespective of the cover in the catchment. A positive relationship exists between sediment yield and annual rainfall amount. The topography of the catchment determines the flow pathways of the overland flow and hence the erosion of the individual spatial units.

The model predicts the spatially and temporally variable patterns and rates of sediment as influenced by the vegetation cover, topography, and rainfall. The model simulations demonstrate that the runoff generated and the sediment yield decrease with increasing vegetation cover over a long-term period. This is particularly the case for low-intensity storms. For large storms the effect of cover is reduced considerably. The fluctuations in the vegetation cover reflect those of the rainfall and show the dependence of recovery on both rainfall amount and history.

- The rainfall intensity plays the most crucial role in the generation of runoff and in the production of sediment yield in the catchment. A positive relationship also exists between sediment yield and annual rainfall amount.
- The runoff and sediment yield simulated will generally decrease with increasing vegetation cover over time. However, because of the variations in the rainfall amounts and intensities, the runoff and hence sediment yield can also vary and have very high values even when the catchment is fully vegetated. This is because vegetation cover is most effective in reducing the runoff and sediment yield for low-intensity storms. Whenever the rainfall intensities increase beyond 10 mm/hr, the reduction in the runoff and sediment yield is greatly reduced.

Implications for management of semi-arid catchments

During years of low rainfall there is corresponding low sediment yield, even for low vegetation cover. The implication of this is that increasing aridity in the semi-arid areas will not necessarily lead to higher sediment yield compared to the wet years. A positive relationship exists between the annual rainfall amount and the modelled sediment yield for annual rainfall of up to 350 mm. These results are consistent with the Langbein and Schumm (1958) curve. The high-magnitude events will always produce high runoff amounts and sediment yield, irrespective of the vegetation cover in the catchment.

From the model results, it has been shown that the spatial vegetation cover can be planned such that the least possible erosion occurs in the catchment. The selection of patterns in which the most vulnerable areas are vegetated can enable the sediment yield in the catchment to be reduced. The importance of modelling the effect of vegetation cover is that it provides an opportunity to compare several possibilities, such that those which provide the most effective measure against soil erosion can be recommended.

Suggestions for further model development

The SEM model developed here is intended to provide comparative sediment yield for different percentages and spatial patterns of vegetation cover. This gives some indication of the order of magnitude of the erosion and enables selection of appropriate vegetation cover in a catchment. With changing technologies and ideas, modelling can never be completed. It must be remembered that models are abstractions of reality, and therefore shortcomings in the model will be a reflection of the current state of knowledge. The exclusion of some processes in the model is because they are not quantifiable or on the basis of pre-existing evidence, rather as a result of restrictions due to scale, time, and lack of data on several processes; and also because of shortcomings in understanding the linkages.

There are always ways of further developing the model structure, either to improve the results or to enable a wider applicability. The following developments are suggested for the model developed here.

- The catchment modelling can be further developed to add channel flow modelling.
- The Strahler ordering system could be improved to allow change to occur in the orders of the flowpaths due to removal of the soil rather than being static.
- Finally, validation of the model for other semi-arid catchments will improve the understanding of ASALs, where lack of proper management could ultimately lead to land degradation.

REFERENCES

Dunne, T., W. E. Dietrich, and M. J. Brunengo. 1978. ‘‘Recent and past erosion rates in semi-arid Kenya’’, *Zeitschrift fur Geomorphologie, Supplement Band*, Vol. 29, pp. 215–230.

Elwell, H. A. and M. A. Stocking. 1976. "Vegetal cover to estimate erosion hazard in Rhodesia", *Geoderma*, Vol. 15, pp. 61–70.

Francis, C. 1990. "Soil erosion and organic matter losses on fallow land", in J. Boardman, I. D. L. Foster, and J. A. Dearing (eds) *Soil Erosion on Agricultural Land.* Chichester: John Wiley & Sons, pp. 331–338.

Francis, C. F. and J. B. Thornes. 1990. "Runoff hydrographs from three Mediterranean vegetation cover types", in J. B. Thornes (ed.) *Vegetation and Erosion*. New York: John Wiley & Sons, pp. 364–384.

Garcia-Ruiz, J. M., T. Lasanta, P. Ruiz-Flano, C. Marti, L. Ortigosa, and C. Gonzalez. 1994. "Soil erosion and desertification as a consequence of farmland abandonment in mountain areas", *Desertification Control Bulletin: A Bulletin of World Events in the Control of Desertification, Restoration of Degraded Lands and Reforestation*, Vol. 25, pp. 27–33.

Garcia-Ruiz, J. M., T. Lasanta, L. Ortigosan, P. Ruiz-Flano, C. Marti, and C. Gonzalez. 1995. "Sediment yield under different land uses in the Spanish Pyrenees", *Mountain Research and Development*, Vol. 15, No. 3, pp. 229–240.

Government of Kenya. 1997. *The National Development Plan 1997–2001*. Nairobi: Ministry of Planning and Development/Government Printer.

Government of Kenya. 2002. *The National Development Plan 2002–2006*. Nairobi: Ministry of Planning and Development/Government Printer.

Hudson, N. 1995. *Soil Conservation*. London: BT Batsford.

Kirkby, M. J. 1990. "A simulation model for desert runoff and erosion", *Erosion, Transport and Deposition Process*, No. 189, pp. 87–104.

Langat, R. K. and J. H. N. Mwangata. 1994. "Range management in Kenya: Progress and status", in D. Herlocker, S. B. Shaabani, and K. S. A. Buijott (eds) *Range Management Handbook of Kenya*, Vol. 1. Nairobi: Ministry of Agriculture, Livestock, and Rural Development/Government Printer, pp. 11–20.

Langbein, W. B. and S. A. Schumm. 1958. "Yield of sediment in relation to mean annual precipitation", *Transactions of the American Geophysical Union*, Vol. 39, pp. 1076–1084.

Lopéz-Bermudez, F. and J. D. Gutierrez-Escudero. 1982. "Estimación de la erosión y aterramiento de embalses en la cuenca hidrográfica del Río Seguro", *Cuadernos de Invesigacion Geográfica*, Vol. VII, pp. 3–18.

Lopéz-Bermudez, F., M. A. Romero-Diaz, J. Martinez-Fernandez, J. M. Martinez-Fernindez, F. Alonso-Sarria, and F. Belmonte-Serrato. 1996. "Field site: Murcia, Spain", *MEDALUS II Project 1 Basic Field Programme Final Report (1991–1995)*, EV5V-CT92-0128, pp. 38–60.

Mitchell, J. K. and G. D. Bubenzer. 1980. "Soil loss estimation", in M. J. Kirkby and R. P. C. Morgan (eds) *Soil Erosion*. Chichester: John Wiley & Sons, pp. 17–62.

Moore, T. R., D. B. Thomas, and R. G. Barber. 1979. "The influence of grass cover on runoff and soil erosion in the Machakos area, Kenya", *Tropical Agriculture* (Trinidad), Vol. 56, pp. 339–344.

Moore, I. D., S. M. Mackay, P. J. Wallbrink, G. J. Burch, and E. M. O'Loughlin. 1986. "Hydrological characteristics and modelling of a small catchment in south-eastern New South Wales: Pre-logging condition", *Journal of Hydrology*, Vol. 83, pp. 307–335.

Obando, J. A. 1996. ‘‘Modelling the impact of land abandonment on runoff and erosion in a semi-arid catchment’’, unpublished PhD thesis, King’s College, University of London.

O’Loughlin, E. M. 1981. ‘‘Saturation regions in catchments and their relations to soil and topographic properties’’, *Journal of Hydrology*, Vol. 53, pp. 229–246.

O’Loughlin, E. M. 1986. ‘‘Prediction of surface saturation zones in natural catchments by topographic analysis’’, *Water Resources Research*, Vol. 22, No. 5, pp. 794–804.

Quinn, P., K. J. Beven, P. Chevallier, and O. Planchon. 1993. ‘‘The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models’’, in K. J. Beven and I. D. Moore (eds) *Terrain Analysis and Distributed Models in Hydrology, Advances in Hydrological Processes*. Chichester: John Wiley & Sons, pp. 63–85.

Romero-Diaz, M. A., F. Lopéz-Bermudez, J. B. Thornes, C. F. Francis, and G. C. Fisher. 1988. ‘‘Variability of overland flow erosion rates in a semi-arid Mediterranean environment under *matorral* cover (Murcia, Spain)’’, *Catena Supplement*, Vol. 13, pp. 1–14.

Conclusion

Sustainable development and headwaters in India and Africa: A summing up

Martin J. Haigh

Introduction

For some decades, the talk has been that our society is driving our planet along a collision course with environmental crisis. Our economies are consuming much more than the earth can provide and our profligate lifestyle is laying waste to our lands. Our society is using up the capital of the earth when it should be living from the interest. Our current way of life is not sustainable. Equally, our society recognizes that it has an obligation to pass to future generations a world that is as productive and full of potential as the one it inherited. R. Y. Singh begins his chapter with an African proverb: "The earth is not ours, it is a treasure we hold in trust for our children and their children." This generation should not allow itself to become a burden upon the welfare of future generations. Nevertheless, this seems to be what will occur.

Overview of land and soil degradation

GLASOD (Global Assessment of Soil Degradation) was the first systematic attempt to produce a global overview of soil and land degradation (Oldeman, Hakkeling, and Sombroek, 1991). Since, fundamentally, there are insufficient data for all but a tiny fraction of the earth's surface, much of this survey had to be based on guesswork and estimation (Oldeman, 1994). Nevertheless, GLASOD provides our best benchmark, and suggests that the global extent of land degradation is about 1,965 million hectares, about 15 per cent of the world's 13,000 million hectares of land and perhaps 22 per cent of the agricultural land base (Bridges and Oldeman, 2001). Water erosion is cited the primary cause across almost 11,000 million hectares, and wind erosion on about half this amount.

Soil compaction is often named as the major cause for land degradation by water erosion – because small changes in the soil's architecture can result in large-scale changes in a soil's ability to absorb potentially erosive rainwater (Shaxson, 1999). Soil physical damage is an increasingly serious problem for agriculture. Worldwide, the productivity of 83.3 million hectares of land may be affected (Bridges and Oldeman, 2001). However, soil and subsoil compaction is difficult to measure and there could be a huge underestimation of the problem (Horn, van den Akker, and Arvidsson, 2000). Recent years have seen a threefold to fourfold increase in both the size of farm machinery and the frequency of trafficking across agricultural lands. This has placed more loading and more stress on their soils, both surface and subsurface. The consequences include reduced agricultural production and accelerated runoff and erosion from affected lands.

Earlier estimates suggested that, worldwide, perhaps 12 million hectares of degraded arable land are said to be abandoned annually due to unsustainable farming practices (Pimentel *et al.*, 1995). Back in 1984, Brown and Wolf (1984: 22–23) guestimated that the world was losing "around 28 billion tons" of soil in excess of soil formation from its 1,270 million hectares of cropland. Allowing each acre approximately 180 mm of topsoil, this suggested a decennial loss rate of 7 per cent, which if true would eliminate half the world's productive topsoil before 2025. This mining away of the world's productive topsoil was called the "quiet crisis" in the world economy, because the changes involved are so tiny in the context of each annual agricultural cycle, yet potentially so disastrous when multiplied across several decades.

Today it is suggested that, on the global scale, the loss of "75 billion tons" of topsoil to erosion each year costs each person on the planet the equivalent of $70 each year in lost production (Eswaran, Lal, and Reich, 2001). Yield reduction in Africa due to past erosion is estimated as 8 per cent overall. Many writers contest the link between erosion and yield reduction and soil loss, noting that biological productivity depends more on the quality of the soil that remains in the field than that lost in erosion (Shaxson, 1999; Hellin, in press). Nevertheless, the fact remains that the topsoils which are lost to erosion or damaged by physical or soil chemical degradation rank with the most productive and the most critical to people who depend on them for their livelihoods.

Water shortage

The preceding section describes the global problems of land degradation. This volume, however, focuses on one of its consequences, which is water shortage. Shisanya and Kwena demonstrate how much time and effort the daily collection of water may cost, even in locations where stress is not especially severe. Opere quotes the World Water Council: "In 1950, only 12 countries with 20 million people faced water shortages; by 1990 it was 26 countries with 300 million people; by 2050 it is projected to be as many as 65 countries with 7 billion people, or about 60 per cent of the world's population, mainly in the developing countries" (cf. Ait Kadi, Shady, and Szollosi-Nagy, 1997: 1; Nairobi Declaration items 11, 12, and 22 in Jansky, Krecek, and Haigh, 2003). A shortage of water and lands damaged by soil degradation and erosion – these are hardly the greatest gifts this generation could give to the future. Hence the current emphasis on the need for sustainable development, which UNESCO defines as locally relevant and culturally appropriate development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

However, as UN Secretary-General Kofi Annan (2001: 2) comments: "Sustainable development will not happen of its own accord. We need a break with the harmful practices of the past." As long ago as January 1990, scientific leaders at the Global Forum of Spiritual and Parliamentary Leaders in Moscow commented: "We are close to committing – many would argue that we are already committing … 'crimes against Creation'", and pointed out that "the environmental crisis requires radical changes not only in public policy but also in individual behaviour" (Cremo and Goswami, 1995: 37). People rarely intend to create environmental problems. They result "as the sum of a myriad of seemingly miniscule individual actions … [but] motive is irrelevant to environmental impacts. It is everyone's job to make the potential consequence of our behaviour conscious – even if ignorance or denial is the politically simpler 'solution'." (Schneider, 1996: 6). Capra (1996: 4), thinking more on this point, suggests that the "environmental degradation … ethnic and tribal violence that has become the main characteristic [of our era should be seen as] different facets of one single crisis, which is largely a crisis of perception. It derives from the fact that most of us, and especially our large social institutions, subscribe to the concepts of an outdated worldview.'' The challenge ahead is that of ''learning how to make decisions that consider the long-term future of the economy, ecology and equity of all communities'' (UN, 2003: 4).

Sustainable management of headwater resources

This book and the conference upon which it was based addressed the sustainable development of water resources, especially in Africa and South Asia. Its work tackles two dimensions of these problems. The first concerns the social processes of sustainable development and efforts being made to transform the worldview that dominates research, global commerce, and ideology, that permits land degradation and desertification, into something that can both meet the aspirations of communities and allow them to ''live as though the future matters''. The second concerns the science. The conclusion of the quote from Schneider (1996: 6) reads ''Ignorance of the laws of nature is no excuse.''

Hence, several contributors have struggled to understand how the processes of nature affect their regions, both in the present and in the past. For example, Subramanian evaluates the water chemistry of the Ganges and Brahmaputra Rivers, finding that they are not so different from the world's other large rivers, even if the discharge is monsoon controlled. He finds that gross sediment erosion and accumulation rates reflect a combination of present hydrological and long-term tectonic processes rather than any human impacts.

Three contributions build and evaluate technical models for the examination of local environmental changes. Onyando and Chemelil work on flood prediction for small ungauged catchments. Their case study examines five catchments in the headwaters of the River Ewaso Ng'iro, which rises on Mount Kenya and flows north-eastwards through the Lorian Swamp. It shows that combining the SCS curve number model for runoff generation and the Nash cascade model for runoff routing allows the creation of a conceptual rainfall-runoff model which can satisfactorily simulate flood hydrographs. However, the method is not applied. Onywere uses GIS techniques for the evaluation of slopes around Lake Bogoria (Ramsar Site 1097), a wetland of international importance in Kenya. This region, a major tourist destination because of its flocks of flamingoes, its geysers, and its scenic beauty, is also the habitat for the Jemp and Tugen peoples, who rely on its natural resources for food. The area is suffering severe land degradation and the lake ecosystem, which supports its tourist industry and biodiversity significance, is threatened by agricultural pollutants. GIS is put forward as a way of evaluating the problem, but no insights from its application are offered. Finally, Obando attempts to model the impacts of human migration and scrub clearance in semi-arid Kenya. The model suggests that runoff and sediment yield generally decrease with increasing vegetation, that a positive relationship exists between the annual rainfall amount and sediment yield for annual rainfalls < 350 mm, that large-magnitude events tend to produce high sediment irrespective of the vegetation, and that for long, dry periods, low sediment yield is produced. This implies that increasing aridity will not necessarily lead to higher erosion rates. Alone of the three chapters in this cluster, Obando converts the potential of the model into some useful conclusions. However, whatever the potential of such modelling techniques, these three chapters also demonstrate their pitfall. Beloved though they are by academics, models tend to divorce the modeller from the reality on the ground. The model becomes of the focus of the effort rather than the problems it should resolve. Possibly, there is a lesson for all researchers in this?

Meanwhile, the concern lurking behind the analyses of most authors is the impact of climatic change (IPCC, 1996). Gathenya calls global warming ‘‘the most profound global threat facing humanity in this millennium’’. A recent report suggests that these processes are already moving rapidly, and perhaps twice as fast as previously suspected (SAPA-AFP, 2005).

Gathenya, also a modeller, proposes a methodology for evaluating the impact of climate change on the water balance of a catchment, illustrated by a case study of Kenya’s Thika catchment (area 1,852 km^2). This catchment provides water to Nairobi and Thika towns and several irrigation projects. Here, a change in annual temperature of +2–4°C, relative humidity of >7 per cent, and annual rainfall of about −9 per cent for an average annual rainfall of 1,200 mm is predicted if carbon dioxide levels double globally (Cubasch, Hegerl, and Waszkewitz, 1996). The study concludes that the biggest impact would be made by changes in precipitation, which would have the most dramatic effect on river flow depths.

In fact, several chapters in this collection report major changes in the flow of rivers and springs. However, in none of these studies are changes in precipitation detected or changes in climate named as the cause.

Schütt and Thiemann study changes in water levels and sediment accumulation in Lake Abaya, a shallow endorheic lake in southern Ethiopia. The lake-level fluctuations of endorheic basins are considered very useful indicators of climatic fluctuation. However, here, while climate data from the past 50 years show high variability, there seems to be no significant trend. Meanwhile, Lake Abaya’s level decreased between the mid-1970s and 1988 and then recovered until 1992. Since 1992 levels have risen again, perhaps as a result of increased precipitation, possibly related to El Niño.

By contrast, flow in the tributary River Bilate declined steadily throughout the period – mainly because of decreased rainwater infiltration rates caused by changes in vegetation and land use. The driver for this was rapid population growth since the 1970s. This has resulted in new patterns of land ownership, deforestation, scrub clearing, and agricultural intensification, which lead to increased water usage as well as accelerated soil erosion processes and lake sediment deposition (cf. Bruijnzeel, 1990, 2001).

Similar results are reported by Murimi and Prasad, who study Lake Nakuru, another shallow endorheic lake, this time in the Central Rift Valley of Kenya. This highly alkaline lake's depth and area have changed dramatically during the last 100 years. In fact, Murimi and Prasad suspect a cyclical decline in lake levels, but their trend is not statistically significant and, in fact, lake levels have remained fairly steady in recent years. Past lake-level fluctuations are attributed to climatic and/or geologic factors and/or land-use changes in its drainage basin. Here, as in Ethiopia, the research team finds no evidence of secular climatic change or major geological activity. Rather, the most striking changes have been in land use, notably the clearance of forest for the resettlement of 30,000 families in a state agricultural colonization programme.

Once again, the team reports a dramatic decline in local river flow magnitudes in the tributary River Njoro and its sub-basins (1958–1996). Especially marked is an increased frequency of low-flow events. This is manifested across all recurrence intervals and all locations, except perhaps the headwater regions. Murimi and Prasad suggest that these changes are related to surface and subsurface abstractions for domestic and irrigation purposes – a factor which the Lake Abaya team emphasizes less. Murimi and Prasad suspect that groundwater extraction may be a most important factor but they have no reliable data. The team agrees that, while the role of geological processes is not ruled out, most of the current hydrological change is directly attributable to human action.

In Kenya, water supply per person is only 640 m^3 per year, and this is projected to decline to 170 m^3 by 2050 through population growth. Opere considers the Mount Kenya region, where a growing population has increased the need for water for drinking, industrial, urban, and, most important, irrigation uses. However, abstractions are not well managed and, currently, 10 times more water is taken out than official regulations permit. In addition, in many places, not least the upper Ewaso Ng'iro North basin, soil degradation, erosion, and reduced infiltration are extensive.

Once again, Opere's study records a decline in river flows. Since 1960 the Ewaso Ng'iro North River flow data have charted a steady decrease, especially in dry season flow. In 1961 mean annual flow was 82.36 m^3s^{-1} and in 1980 it was 6.8 m^3s^{-1}. Average flow in February's low-flow conditions declined from 9 m^3s^{-1} in the 1960s to 4.59 m^3s^{-1} in the 1970s, 1.29 m^3s^{-1} in the 1980s, and 0.99 m^3s^{-1} in the 1990s.

Such problems are not specific to Africa. Tiwari and Joshi address the sustainable development of water resources in Uttaranchal's Kumaun Himalaya. Here, many are concerned about declining recharge to groundwaters and drought (cf. Chadha, 1989; Mountain Agenda, 1998). For example, studies of the Gaula catchment, below Nainital, found that 45–46 per cent of springs had dried up or become seasonal in recent memory (Valdiya, 1985).

Around 75 per cent of the Kumaun population depend on subsistence(biomass)-based agriculture, and the agricultural area expands each year. Long ago, studies by Singh, Pandey, and Tiwari (1984) showed that the production of each hectare of Himalayan agricultural land depends on subsidies of fodder and fuel from 5–10 ha of local forest lands. In the upper Kosi, only 2.7 ha are available and 60 per cent of these are severely degraded. Overgrazing by cattle is a problem for up to 7 km around each settlement.

Overall, more than 15 per cent of all the Kumaun's watersheds are considered "degraded" (cf. Stocking and Murnaghan, 2001). Local research shows that while runoff from forest land may be very low, that from barren land may be three times and from cultivated land six times greater (cf. Shaxson, 1999). This has led to a lowering of the water table through lack of recharge. Tiwari's study in the Shail catchment of the upper Kosi catchment found that during the last 20–25 years 18 out of 49 natural springs had completely dried up, all nine flourmills had been abandoned due to low water discharge, and stream heads had migrated down valley by an average of 37 m.

Despite this, Tiwari and Joshi argue that there is massive underutilization of the water resource potential. Less than 7 per cent is being used. The case study in the Shail watershed found that while the springs were capable of generating a dry season flow of 210 l/ha/day^{-1}, local people were unable to obtain the 5 l/day^{-1} needed for domestic purposes and many fields that would benefit from irrigation received no water. Overall, irrigation is practised only in valley bottoms and its waters reach only 11 per cent of the Kumaun Himalaya's small resource of agricultural land.

So, Tiwari and Joshi argue for water resource development and a holistic approach. They propose that, as a first step, there is a need for the construction of a natural resources information system (NRIS) at micro-watershed level, using GIS and remotely sensed analysis, appraisal, and mapping to appraise the current state of land, water, and forest resources in their socio-economic contexts. Meanwhile, others in the same area work with local village communities to try and help them solve problems on the ground by improving sanitation, water management, and environmental understanding (Jackson, 1999).

Back in Kenya, a nice survey by Shisanya and Kwena reviews the ways that rural families access their domestic water supply in Kakamega district and offers some more immediate solutions. This study, which surveyed 300 respondents, found that daily water requirements per capita averaged 120 l/day^{-1}, or 20–720 l/day^{-1} per household, depending on family size. Collection involved travel to a water point some 0.5–3.5 km from the home. Most water collectors (56 per cent) travelled less than 0.5 km and few (1 per cent) more than 2.5 km, but on average each household made five trips per day. Shisanya and Kwena note that, officially, the government considers water within a distance of 1.0 km in urban areas and 5.0 km in rural areas to be "within easy reach". However, even here the average time expended in water collection was 127 minutes per day per household. During the International Drinking Water Supply and Sanitation Decade (1981–1990) efforts were made by the Kenyan government and some NGOs to protect some 690 springs in Kakamega. Unfortunately, management and maintenance have since been neglected, resulting in the collapse of some springs and contamination issues. Many springs are contaminated by surface waters that contain agrochemical residues, household garbage, and carrion.

Currently, only 11 per cent of respondents pay for the delivery of their water. However, 77 per cent would be willing to pay for the provision of a safe water supply. Among those unwilling to pay, many felt that water is a free gift from God (29 per cent), while others had no income with which to pay (27 per cent).

Inevitably, most water carrying is done by adult women (46 per cent) and children < 18 years old (50 per cent), the majority of whom were also female, especially in the older age ranges. Only 4 per cent of households used hired labour. Shisanya and Kwena point out that the opportunity costs associated with securing water are large: survey respondents said they could earn Kshs50–60 for the same two hours spent as a casual labourer – a fact that came out very clearly during focus group discussions. Shisanya and Kwena emphasize that the empowerment of women is an important prerequisite to dealing with issues of the accessibility of water and water quality. These thoughts motivated items 16, 19, and 22 of the Nairobi Declaration (Janksy, Krecek, and Haigh, 2003).

Special cases: Rangelands and wetlands in headwater regions

Three chapters deal with the problems of sustainable development in two special headwater environments, both of which lay claim to meriting greater attention. Rajwar focuses on the sustainable development of rangelands in the Himalayan headwaters of Uttaranchal, India. Rangelands are lands that, while unsuited for cultivation, have important functions as sources of forage for free-ranging animals. These lands are as widespread in the Himalaya as in other headwater areas, and extend from the Siwalik foothills to the trans-Himalaya and Tibet. They are reserves of cultural diversity through their special pastoral communities, and also of biodiversity. They provide habitats for many plant species, some quite endangered, including some of medicinal importance (Rajwar, 1993). They have important impacts on water quality, water supply for irrigation downstream, and for sustainable power generation through hydroelectricity. They also attract visitors, fuelling a tourist industry that may not only improve local livelihoods but can also assist overall economic development.

For Rajwar, the art and science of range management is that of ''optimizing biomass productivity for the benefit of society through the manipulation of resources: biological, physical, and social''. This is explored through research on the productivity of rangelands used by six villages, 800 people in total, in the Nanda Devi Biosphere Reserve's buffer zone in Chamoli district, Uttaranchal.

Many people in this region are semi-nomadic: in only two villages did the people remain inside the buffer zone of the biosphere reserve throughout the year. Three villages were local migrants, moving to and from the buffer zone over a distance of not more than 5 km. One village had a migrating distance of more than 40 km. Despite this, grazing pressure was greatest within 3 km of the village boundary, and it was within this zone, mainly, that significant overgrazing was taking place. Rajwar proposes that the management of these lands should be based on determinations of forage production and carrying capacity, and that grazing access should be restricted to minimize damage to pastures and preserve plant diversity (cf. Joshi and Srivastava, 1991). He also recommends greater use of crop residues as fodder, and a search for ways of reducing conflicts between the pastoralists and wildlife.

As elsewhere in these headwaters, all the villages were in decline, with each year there being fewer occupied houses in the summer. The reason was the emigration of younger people, gone to seek work in the towns and lowlands. So Rajwar argues that the social conditions of the pastoralists and their problems should be considered in management plans. However, he is able to offer no immediate remedies, and the real conclusion is that it may be easier to effect sustainability in the biophysical than in the social component of these mountain headwaters.

Like Rajwar, Wood and Dixon tackle a special, yet typical, headwater habitat – wetlands. In the Nile headwaters of Ethiopia and Rwanda, wetlands are small (1.4–5.0 per cent) parts of the total land area, but are significant aspects of their sustainable development. In these countries, wetlands provide critical water storage that helps sustain the flow of streams and rivers. They are also vital elements in the local agroecosystem. So the challenge is to balance local needs while preserving hydrological functionality.

Unfortunately, agricultural development often results in drainage and the subsequent degradation of the wetlands. The lower water table makes crop cultivation possible, but the installation of drains accelerates runoff, often leading to channel incision and erosion, and also reduces groundwater recharge. Eventually, desiccation causes the oxidation of humus, soil compaction, and soil degradation. These changes affect the livelihoods of not only local cultivators but also those affected by the hydrological changes downstream. In fact, similar processes affect wetlands elsewhere (cf. Krecek and Haigh, in press; Dugan, 1990).

Wood argues that wetlands may become more important as land degradation reduces the infiltration and groundwater storage capacity of the interfluves. Even today, in many parts of the developing world the capacity of wetlands to act as "sponges" and maintain base flows during dry periods is critical to the livelihoods and subsistence of whole communities (Balek and Perry, 1973; Balek, in press). Wood agrees, arguing that while much attention has been devoted to the role of land degradation in accelerating runoff and causing more variable flow downstream (cf. Haigh, Jansky, and Hellin, 2004; Bridges *et al.*, 2001; Newson, 1992), little attention has been given to the important role played by wetlands in storing water, regulating stream flow, and maybe reducing floodwater peaks (Maltby, 1986; Dugan, 1990).

An appreciation of this reality led to the generation of item 18 in the Nairobi Declaration (Jansky, Krecek, and Haigh, 2003; Haigh, 2004). This launched a major workshop that explored the role of headwater wetlands worldwide. The workshop (see below) was dominated by scientific reports, and equally came to a social scientific conclusion – that empowering local communities for effective environmental management was the best way ahead.

Exploring the role of wetlands in a headwater context

This section presents results from NATO Advanced Research Workshop 979810: Environmental Role of Wetlands, held in Marienbad, Czech Republic, in December 2003 (Krecek and Haigh, in press).

This meeting was called to solve an important practical problem for watershed managers: how to manage watersheds that contained significant wetland areas, especially wetland areas in the upper catchment and headwater areas. The problem is compounded by the fact that much current research into wetlands is difficult to apply to watershed management because it has tended to focus on the internal dynamics of the wetland – as a resource for biodiversity, economic development, or hydrological phenomena – rather than the issues that help place wetlands in their wider contexts (Soulsby *et al.*, 2003). This problem was earlier identified in the Nairobi Declaration for the International Year of Freshwater 2003 (Jansky, Krecek, and Haigh, 2003), which provided the mandate for the organization of this NATO Advanced Research Workshop, convened with major assistance from the International Association on Headwater Control.

Several aspects of the Nairobi Declaration were explored by this meeting (Jansky, Krecek, and Haigh, 2003; Haigh, 2004). These included item 13: "Sustainable development should be the baseline for all environmental policy, planning, management, practice, education and law, in headwater regions"; item 17: "Greater effort should be devoted to the refinement of methods for generating and sharing the appropriate and reliable information needed for environmental research, planning and management and also for the transfer of appropriate low cost technologies, especially with respect to issues that relate to 'cushioning' human populations against the impacts of environmental hazards and extremes"; and item 18: "Greater attention needs to be paid to the special roles and hydrological functions of headwater wetlands and peatlands – and this should be a special focus for a future headwater workshop – and also to the impacts of anthropogenic processes on watershed functions in headwater regions."

An assessment of the area of headwater wetlands was carried out using CORINE data (EEA, 2005) for the EU15 countries (excluding Sweden) plus Poland, Estonia, Latvia, Lithuania, the Czech Republic, Slovakia, Slovenia, Hungary, Bulgaria, Romania, Bosnia-Herzegovina, Albania, and Macedonia. This EU15 survey determined that headwaters amount to 1 million hectares (27 per cent of the total land area), and wetlands in headwaters to 10,600 ha, about 1 per cent of the headwater area (Paracchini and Vogt, in press). In higher latitudes, however, wetlands cover much greater proportions of the land, including the headwaters – 14 per cent (1.48 million km^2) in Canada, and greater proportions in nations such as Belarus and the Baltic nations included in the EU15 survey.

Workshop discussion foci included the sustainable management of the peatlands of headwater regions, especially in northern Europe, and particularly with respect to the role of hydrology, drainage, and forestation, the interactions between wetlands and climatic change, the utility of wetlands in the management of environmental hazards, and the role played by stakeholders, especially the locally resident communities of these regions.

Results from hydrological studies are ambiguous. The traditional view, that peatlands adsorb and store rainwater, is contested. Undisturbed peat wetlands are poor aquifers. They act mainly as surface flow systems that do little to moderate floods unless they are drained. Drainage of peatland results in drier soil covers and reduced evaporation. This, in turn, generates higher annual runoff. After drainage, peatland may moderate flood flow in dry conditions because of increased soil storage, but as time passes after drainage this effect diminishes. Eventually, peat compaction and decomposition cause the runoff to increase again. Drainage ditches also increase the speed of runoff and encourage erosion. However, the main hydrological effect of mire drainage is related more to changes in the pathways of water movement through the subsurface than to changes in water balance. Forestation does change the water balance: evapotranspiration increases and runoff is reduced. Snow-melt runoff also falls due to decreased snow melting rates and reduced snow accumulation. Overgrazing, trampling, and burning encourage accelerated runoff and erosion. Coal mining is a factor in the destruction of wetlands and, through subsidence, in the creation of new wetlands. Peat headwaters produce storm runoff that is acidic, but drainage increases the chemical loading of most ions and reduces pH. Burning moderates pH, but forestation encourages acidification. In northern Canada's permafrost area, warming by 1°C has occurred during the past 13 years while in the same period air temperatures have cooled or remained stable. Since the depth of permafrost in wetlands/peatlands can exceed 12 m, thawing increased the water storage capacity by as much as 60 per cent in one case study area. This could result in reduced peak flows following snow-melt and high-rainfall events and increased year-round base flows in affected basins.

Disturbed peat soils are sinks for methane, while undrained peatlands are sources. However, in general peatlands are net sinks for C, N, and many other environmental chemicals, although environmental changes can reverse this effect. Blanket peatlands are often sources for sediments, as in the UK, but most headwater wetlands tend to be net sinks for sediments as well as nutrients – as demonstrated by the Hula Valley wetland of Israel. Newly constructed headwater wetlands can be used to decrease sedimentation – as at Madan Reservoir, Bulgaria. However, small landslide-dammed lakes in mountains undergo rapid eutrophication and are complex, little-understood wetland habitats. The control of eutrophication processes by planktonic communities was explored in a case study at Dragichevo, Bulgaria.

Intense siltation is a major problem for environmental management around Lake Alleghe, Italy, an alpine landslide-dammed lake formed in 1771. Present problems arise from the need to remove and relocate deposited sediment in order to restore satisfactory environmental conditions and hydrological functions. The catastrophic impacts of landslide/mudflow activity and the possibilities of landslide forecasting were discussed in the context of the ‘‘Log pod Mangartom’’ mudflow of the Upper Soca Valley, Slovenia.

The debate concerning the role and function of Africa headwater wetlands echoes that in Europe. African headwater wetlands, ‘‘dambos’’, play a significant role in the hydrological regime of rivers. Dambos are seasonally waterlogged, grass-covered, treeless areas that remain wet in the dry season because of slow subsurface drainage from the upland areas between dambos. Outside dambos, much precipitation is lost as evapotranspiration and the land is relatively dry. Despite some scientific assertion to the contrary, dambos help conserve rainwater and sustain dry season river flows. In western Ethiopia, local communities gain benefits from such wetlands, including thatching materials, medicinal plants, springwater, seasonal grazing, craft materials, and arable land. Here, demographic, economic, and land-use pressures are leading to increased agricultural use of wetlands and, in many cases, to their degradation. However, potentially sustainable management regimes with mixed land use have been developed which seem to offer possibilities of maintaining many of the hydrological functions of these areas and simultaneously meeting community needs. It should be possible to construct sustainable land-use regimes based on local knowledge of wetland management and local land management institutions.

Community education will be a critical aspect of promoting sustainable development in headwater regions. There is a need to ensure that the concerns and practices of water resources management are more widely and formally included in the new educational agenda being promoted in connection with the launch of the UN’s Decade of Education for Sustainable Development (2005–2014). Two models of ESD were discussed. The NGO Earthwatch’s model promotes public education by sponsoring the engagement of community volunteers in scientific research projects. By contrast, the environmental education centre in Galtur in the Austrian Alps stresses the dual role of the headwater as a resource and a hazard, and considers how this approach can be transferred to other headwater areas. The Pian di Spagna wetland, in the Italian Alps, is a case in point. A flood-prone area until 1858, when the Adda River was canalized into Lake Como, this became a Ramsar reserve in 1996 because of its ecological value. However, the area is affected by critical concentrations of chromium, and little attention has been paid to the rehabilitation of the flood-prone areas while local vulnerability is increasing.

It is concluded that, in general, there is a need for better coordination between those planning sector-specific environmental protection measures. In addition, better environmental management understanding is required to maximize the benefits to stakeholders in upland wetlands and minimize potential negative impacts due to emissions of greenhouse gases, hydrological changes involving flooding, water chemistry, and sedimentation. There remains a need to assess the continuing role of these wetlands in current and future land-use systems, especially agriculture, forestry, water resource management, tourism, and nature conservation.

The final plenary discussion commended the following action: work towards improving access to relevant data sources internationally, activities that would help keep this interest group linked, and interacting via further conferences and publications, plus greater and more sustained engagement with local communities and stakeholders. It was agreed that effective environmental management for sustainability should be led by the local communities wherever possible, but that this had implications for the provision of environmental education.

Beyond this, broad conclusions were adopted. It was agreed that there was a major underestimation of the roles played by wetlands in headwater regions in most national action plans. A new inventory was needed, perhaps constructed on the mapping methodologies described by Paracchini and Vogt (in press). In contrast to lowland wetlands, the hydrological role of headwater wetlands is neither fully understood nor properly recognized. Unfortunately, the existing system controlling wetlands (namely the conservation and protection of Ramsar national sites) tends to treat wetlands in isolation rather than in context, and emphasizes their biodiversity role more than their wider environmental functions. Better and more effective management requires better understanding of the complete role they play and the holistic integration of their attributes – biological, hydrological, and socio-economic – into watershed management planning. Enhancing the husbandry of headwater wetlands within integrated watershed programmes may be achieved through measures such as better assessment of the critical attributes of headwater wetlands that control their various functions, better community and citizen education that might help drive more effective participatory processes in watershed management, and by granting wetlands greater emphasis in planning processes.

Other aspects of wetland management

However, Dixon and Wood go beyond such notions by recognizing the sophisticated systems developed by some local communities for wetland management. In the past, while studies have increasingly recognized the dependence of local communities on wetlands, the local knowledge on which indigenous practices are based has often been dismissed as outdated, unproductive, and disorganized. However, rural people's land management systems emerge from a long-term process of trial and error extending across several generations, so whatever the knowledge base may be, it has proved that it can work and has worked in the past. Today, leading-edge researchers in rural development recognize that rural farmers should not be seen merely as subjects for the passive adoption of external ideas and technologies. Instead, they should be appreciated as skilful resource managers, problem-solvers, and innovators who work hard to get the best from their land (Hellin, in press).

In south-west Ethiopia's Illubabor zone, wetlands are a significant resource used by almost every household. A long history of wetland use has led to the development of deep local knowledge and effective local management practices that contribute to the sustainable use of these wetlands. For example, recognizing that flooding is the key to the sustainable harvesting of wetland products, farmers employ a system of drainage-channel blocking. Channels are blocked after each crop harvest, and the consequent flooding fosters the decomposition of crop residues, weed control, and the regeneration of the natural sedge vegetation. This also helps to retain water and allows the settlement of sediments that help restore soil fertility. Despite such activity, should agricultural yields decline too far, farmers cease cultivation, block the drainage channels, and leaving the wetland fallow for several years until the natural vegetation regenerates and the fertility of the soil recovers.

Sometimes this understanding is supported by indigenous management structures. For example, the Tulla system of the Oromo people appointed a community elder as Abba Laga or "water father" to coordinate the use of the wetlands. This official was empowered to organize drainage and guarding, and the removal of farmers who did not farm appropriately.

In recent years, a variety of government and market forces have expanded wetland drainage schemes from the wetland margins to the whole area. There has been an expansion of cash-cropping and cattle grazing. However, despite the intensification of land use, land degradation problems are conspicuously associated with places where the management schemes are recent or externally imposed. In many cases, sustainable management is associated with long-standing indigenous systems.

This situation is more evident in Rwanda, where both drainage and double-cropping agricultural systems are expanding fast, but where issues of hydrological sustainability and agricultural sustainability are not so clearly addressed. Here, there is a serious threat that the wetland resources will be seriously degraded and their role in national food and water security dramatically reduced.

Recently, the conservation of natural wetland functions and values has been seen as a better goal than reclamation by drainage. The Ramsar Convention advocates the principles of "wise use" and "sustainable utilization'' of wetland resources (Ramsar Convention Bureau, 2000). Whilst such approaches have recognized the dependence of local communities on wetlands, little attention has been given to the knowledge on which indigenous practices are based (Agrawal, 1995). The concept of community involvement has been synonymous with community cooperation in achieving conservation-orientated management goals, rather than the incorporation and empowerment of indigenous knowledge and community control over wetland management strategies. The challenge ahead is to identify successful local wetland management systems and help them keep pace with the changing pressures from outside. To achieve this, the institutions and mechanisms for information exchange must be strengthened to include all wetland stakeholders and, possibly, to define a role for external expertise in strengthening the capacity of the local communities to develop their own solutions to problems.

In this, the guiding principle must be that local communities gain benefit, such as perennial clean springwater and craft or medicinal materials, from their wetlands so that they have vested interests in protecting these areas and maintaining a sustainable land-use regime.

Wood and Dixon recommend four steps forward, the first of which is consciousness-raising to bring the issue of wetland management on to local and national agendas. Ultimately, wetland management will succeed in sustaining the flow of large basins such as the Nile if there is multi-country coordination of appropriate land use. Here, the special role of wetlands must be understood and considered. Second, a holistic land-use model should be developed to ensure that wetlands operate efficiently as multifunctional water storage areas. Third, the empowerment of local wetland management institutions should be recognized as a valid way of mitigating the pressures on wetland communities to overdevelop and degrade their lands. Democratic local institutions, linked to grassroot local community structures, can coordinate the use and management of wetlands and their catchments and help preserve the local sense of ownership over the welfare of the land. Dixon reports that, in Ethiopia, the farmers acknowledged a shared responsibility for wetland management. He also highlights a need for improved communication between isolated wetland communities. His study found that there was little sharing of wetland knowledge between different wetland communities, and the mechanisms for spreading new knowledge were underdeveloped.

Dixon concludes that local knowledge allows the sustainable management of many wetlands in Illubabor, and that while some degraded wetlands exist, these are fewer than might be expected. His main concern is this indigenous system may need help to cope with future environmental or socio-economic changes. Its pace is too slow moving, and it is heavily dependent upon its economic and socio-political contexts. Illubabor's wetland communities are becoming more vulnerable to the negative impacts of resource constraint and top-down prescriptive policies of agricultural extension. Land tenure and access rights are also unclear, which deters some farmers from investing in long-term management strategies. Hence, it is unwise to rely too much on some local communities' abilities to continue to manage wetlands in a sustainable manner.

As R. Y. Singh argues, "Now is the time ... to engage further with ... discourses such as environmental justice, political ecology, environmental politics, and environmental ethics." Sadly, the body of his contribution deals with hydrographic measurements made from topographic sheets, and is completely divorced from its own opening and closing sentiments. In this, the work demonstrates the gap between the conventions of research and the realities of hydrological management in the field.

Summing up

The conclusion to this book, and to the discussions at the larger conference from which this collection of papers is abstracted, is the Nairobi Declaration for the International Year of Freshwater 2003 (Janksy, Krecek, and Haigh, 2003; Haigh, 2004; Chapter 1 in this volume). However, the small sample of reports published here raises several additional issues.

Water supply is a major linking theme (Nairobi Declaration, items 2–8 and 11). Several chapters express concern about the decline of flows in rivers and springs and increasing susceptibility of drought, while that of Shisanya and Kwena demonstrates just how heavy, already, are the current costs of daily water collection. Several chapters search for the impacts of global warming and secular climatic change. Subramanian demonstrates that at the macro scale, water quality and chemistry are controlled by geology, tectonic processes, and hydrology. However, at the level of the individual catchment and the places and scales where people actually live, the main process driving negative environmental change is the human impact. Case studies from both Africa and India compile evidence of the unsustainable development of land and water resources which has resulted in land degradation and the desiccation of affected landscapes (cf. Stocking and Murnaghan, 2001; Shaxson, 1999; Mountain Agenda, 1998). Three aspects of the human impact are involved in this situation. The first is population expansion and the spread of people into new areas, causing deforestation, scrub clearance, and soil degradation processes that have reduced groundwater recharge. The second is the increasing demand for water for irrigation and other uses, which has led to increased, often unofficial and excessive, groundwater extraction and depletion. Together, these processes are the main reason for the decline of river flow, and especially for the severe reduction of flow in low-flow conditions. The third factor, explored by Rajwar, Dixon, and Wood, is the condition of traditional management systems. It is agreed that these systems engage large amounts of experience and expertise for the sustainable management of headwater resources. There is also evidence that where these systems are working, they have managed to protect the environment from processes that have caused degradation elsewhere. Unfortunately, both of the systems examined here are at or beyond their own limits. The rangeland pastoralist communities of Uttaranchal are suffering rapid decline due to emigration. Those in Ethiopia are increasingly in danger of being overwhelmed by the pace and scale of social and economic changes affecting their regions.

All of these reports underline the vital need for researchers to work with the community of land users to promote better land husbandry and to help those communities help themselves to adapt to a changing world. Shaxson *et al.* (1997: 1) talk about "collaborative efforts which are interdisciplinary, supportive of farmers' aspirations, and based on joint learning" (Nairobi Declaration, items 16, 22, and 23). This Nairobi conference on the "Sustainable Management of Headwater Resources", the fifth international conference on headwaters, also provided an important benchmark in the evolution of the Headwater Control Movement. It marked the moment when that movement publicly changed its aspiration, from controlling headwater habitats to fostering headwater *swaraj* – headwater self-control.

Wetlands were a special concern of this conference and the subject of a major follow-up workshop (Nairobi Declaration item 18; see above). The upshot of this was agreement that the role of wetlands in headwater regions was underplayed in most national action plans. An inventory was needed (cf. Paracchini and Vogt, in press). However, the hydrological role of headwater wetlands is not fully understood, although the existing system controlling wetlands (Ramsar national sites), which tends to treat wetlands in isolation rather than in context, is unhelpful. Better and more effective management requires more holistic integration of their many functions – biological, hydrological and especially socio-economic – into watershed management planning. Enhancing the husbandry of headwater wetlands also requires better community and citizen education to help drive more effectively empowered community participation in watershed management. These mechanisms of community-based watershed management have been explored by another follow-up meeting, which has also emphasized the roles of community-based NGOs and citizens groups (Zlatic, Kostadinov, and Dragovic, 2004).

However, as Kofi Annan's Dhaka speech argues, "Our biggest challenge in this new century is to take an idea that sounds abstract – sustainable development – and turn it into reality for all the world's people'' (Annan, 2001: 2). For more than a decade, the Headwater Control Movement has sought to unite the perspectives of the researcher, the field practitioner, and the policy-maker. Hellin (in press) concludes that, today, the pendulum may have swung too far from attention to the biophysical aspects of sustainable development towards the social and economic. However, the papers from this Nairobi Conference suggest that there is still a great deal more to be done. The problem, however, may be less in the effort devoted to the scientific aspects of headwaters than in the mind-sets of those who undertake the research. In brief, too little of the work being done is directly relevant to the problems of sustainable development. Too many researchers are content to produce results of vague academic significance. Too few bother to ground truth in their work, especially by finding out information that the people actually engaged in the development, hopefully sustainable development, of headwater regions really need. As Capra (1996) suggests, the problems arise from institutional acceptance of an outdated worldview, which no doubt is inherited from an ''Oxbridge élitism'' of former colonial times.

Today, the fashion for many universities in the West is to reify ''blue-sky research'', by which is meant research that has no immediate practical value. Of course, every society needs its dreamers and, no doubt, from such unconstrained investigations important new understandings will emerge. However, the downside of this, of course, is that practically useful research is seen as a ''low-brow'' activity, suitable only for those in lower-ranked universities and technical institutes. By extension, useful practical work is something only done by low-brow people and servants. The attitudes that built the ivory tower of academia are alive and well and, as far as headwater management is concerned, very unhelpful.

India has long nurtured a notion that the best people are those who retreat from the world of action. Like the ''élite'' Western academic, those who aspire to the path of knowledge think high thoughts but remain aloof from practical labour. However, from Swami Vivekananda, Mahatma Gandhi, and Acharya Vinoba Bhave, India's intellectual leaders have commended the life of engagement, service undertaken from a sense of duty, without attachment to the fruits of that action, the path of karma (Vivekananda, 1907). In the Bhagavadgita, Lord Krishna's message to the heroic Arjuna is that it would be wrong for him to step away from his duty, however difficult. Instead, he must act selflessly to do the works that are necessary for preservation of world order (*loka-samgraha*, Bhagavadgita 3, 20; Gandhi, 1926). Bhave (1986: 93) argues: ''The karma-yogi lives without ego and is one with the community around ... Through action, the karma-yogi attains a state of being that is pure, action is a form of prayer.'' Gandhi was personally committed to the useful work he called ''bread labour''; memorably, he used to spin cloth each day (Gandhi, 1969: 330–333). His last words in *Hindu Dharma* invoke a follower to discard the saffron robe and go and do something useful for the community (Gandhi, 1978: 158–160).

Payutto (1995: 27–29) comments:

> The real life problems in our society are in need of an immediate answer or remedy – now, in this present life ... Even though science is capable of providing many efficient answers, it is hampered by being ''too little'' and ''too late'' ... Science on its own is not capable of solving humankind's problems, science and technology do not encourage good behaviour ... they suffer from ''funnel vision'' in that they seek to amass data but do not provide us with the knowledge of how to lead a good life ...

The problem is magnified because our dominant and increasingly global culture is also based on highly suspect, unhelpful ideas (Jackson, 2003). For example, Berry (1999: 102) notes:

> Our legal system fosters a sense of human rights, with other than human beings having no inherent rights. Our economic system is based on the exploitation of the Earth in all its geobiological systems. Commercial rights to profit prevail over urgent need of natural systems for survival.

Genuine sustainability will require that our society disengages from such thinking. At present, nothing takes priority over our immediate social needs and human values. Berry (1999: 56) argues that our route towards becoming a viable species is ''to shift from a human-centred to an Earth-centred norm of reality and value''. In fact, this is not a negation of concern for humans but an enlightened self-interest that seeks to preserve the whole human habitat. As Kofi Annan (2004: 1) points out: ''Our highest priority should be to guarantee the health and effective functioning of the Earth's life support systems – on land, the seas and in the air.'' Rationally, this point of view seems self-evident, yet the reality revealed in these chapters and in the daily media tells a different story.

Kofi Annan (2004: 1) also notes that: ''Every individual ... has an obligation and an interest in changing outlooks through education and by example, thereby helping to end thoughtless or deliberate waste and destruction.'' The Nairobi Declaration (item 20) anticipates the launch of the UN Decade of Education for Sustainable Development 2005–2014 (UN, 2003) by recognizing that sustainable development is not merely an issue for professionals in environmental management and research but an issue for every individual in the community (Haigh, in press). To repeat, Kofi Annan has argued that ‘‘Our biggest challenge in this new century is to take an idea that sounds abstract – sustainable development – and turn it into reality for all the world's people'' (Annan, 2001: 2). This task, more than any science, technology, or even social science, is the real front line for work in the sustainable management of headwater resources.

So, what is needed? Joanna Macy anticipates a ‘‘Great Turning'', something which may be accelerated by educational processes that, first, show the actions that may reduce the damage our species causes to the earth, second show the true causes of environmental unsustainability and their alternatives, and thirdly guide learners towards their construction of a fundamentally new system of values, a new worldview (Macy and Brown, 1998: 17). She suggests that the components of this new worldview are already well known, and include general living system theory, Gaia, deep ecology, spirituality, ecopsychology, and so forth (Macy and Brown, 1998: 22; Cremo and Goswami, 1995; Naess, 1973, 1987). However, the keys are the construction of a new ethic that stresses personal responsibility, practical awareness (that the needs of the whole life-support system must take ultimate priority), and a commitment to create a world fit to be passed on to future generations.

The last word goes to the philosopher Ervin Laszlo (2002: 1):

> The world needs changing. It is not sustainable, and sooner or later it will change. Predicting which way it will change is not the challenge before us, the future is not to be foretold, it is to be created. The challenge is to create a positive future. And that is up to us – to you and me.

REFERENCES

Agrawal, A. 1995. ‘‘Dismantling the divide between indigenous and scientific knowledge'', *Development and Change*, Vol. 26, pp. 413–439.

Ait-Kadi, M., A. Shady, and A. Szollosi-Nagy (eds). 1997. *Water, the World's Common Heritage, Proceedings of the First World Water Forum*. Oxford: Elsevier Science, available at www.worldwatercouncil.org/publications.shtml.

Annan, K. 2001. ‘‘Secretary-General calls for break in political stalemate over environmental issues'', UN Press Release SC/SM/7739, available at www.un.org/News/Press/docs/2001/sgsm7739.doc.htm.

Annan, K. 2004. ‘‘Secretary-General says failure to stop biodiversity loss too awful to contemplate'', UN Press Release SG/SM/9289, ENV/DEV/780,OBV/420, available at www.un.org/News/Press/docs/2004/sgsm9289.doc.htm.

Balek, J. In press. ‘‘Hydrology of wetlands in the headwaters of great African rivers'', in J. Krecek and M. J. Haigh (eds) *Environmental Role of Headwater Wetlands*. Dordrecht: NATO/Kluwer.

Balek, J. and J. E. Perry. 1973. "Hydrology of seasonally inundated African headwater swamps", *Journal of Hydrology*, Vol. 19, pp. 227–249.

Berry, T. M. 1999. *The Great Work*. New York: Bell Tower.

Bhave, V. 1986. *The Intimate and the Ultimate*. Totnes: Green Books/Brahma Vidya Mandir.

Bridges, E. M. and L. R. Oldeman. 2001. "Food production and environmental degradation", in E. M. Bridges, I. D. Hannam, L. R. Oldeman, F. W. T. Penning de Vries, S. Scherr, and S. Sombatpanit (eds) *Response to Land Degradation*. Enfield, NH: Science Publishers, pp. 36–39.

Bridges, E. M., I. D. Hannam, L. R. Oldeman, F. W. T. Penning de Vries, S. Scherr, and S. Sombatpanit (eds). 2001. *Response to Land Degradation*. Enfield, NH: Science Publishers.

Brown, L. and E. C. Wolf. 1984. *Soil Erosion: Quiet Crisis in the World Economy*, Worldwatch Paper 60. Washington, DC: Worldwatch Institute.

Bruijnzeel, L. A. 1990. *Hydrology of Moist Tropical Forests and Effects of Coversion: A State of Knowledge Review*. Paris: UNESCO/IHP.

Bruijnzeel, L. A. 2001. "Hydrology of tropical mountain cloud forests: A reassessment", *Land Use and Water Resources Research*, Vol. 1, pp. 1.1–1.18, available at www.luwr.com.

Capra, F. 1996. *Web of Life: A New Synthesis of Mind and Matter*. London: HarperCollins.

Chadha, S. K. (ed.). 1989. *Environmental Holocaust in the Himalaya*. New Delhi: Ashish Publishing.

Cremo, M. A. and M. Goswami. 1995. *Divine Nature: A Spiritual Perspective on the Environmental Crisis*. Los Angeles: Bhaktivedanta Book Trust, Contemporary Vedic Library.

Cubasch, U., G. C. Hegerl, and J. Waszkewitz. 1996. "Prediction, detection and regional assessment of anthropogenic climate change", *Geophysica*, Vol. 32, pp. 77–96.

Dugan, P. J. 1990. *Wetland Conservation: A Review of Current Issues and Action*. Gland: IUCN.

EEA. 2005. *Data Highlights: CORINE*. Copenhagen: European Environment Agency Data Service, available at http://dataservice.eea.eu.int/dataservice/.

Eswaran, H., R. Lal, and P. R. Reich. 2001. "Land degradation: An overview", in E. M. Bridges, I. D. Hannam, L. R. Oldeman, F. W. T. Penning de Vries, S. Scherr, and S. Sombatpanit (eds) *Response to Land Degradation*. Enfield, NH: Science Publishers, pp. 13–35.

Gandhi, M. K. 1926. *M K Gandhi Interprets the Bhagavadgita*. New Delhi: Orient/Vision Books.

Gandhi, M. K. 1969. "Dignity of labour, bread labour", in S. Narayan (ed.) *The Voice of Truth*. Ahmedabad: Navajivan Trust, pp. 330–335.

Gandhi, M. K. 1978. *Hindu Dharma*. New Delhi: Orient/Vision Books.

Haigh, M. J. 2004. "Sustainable management of headwater resources: The Nairobi 'Headwater' Declaration (2002) and beyond", *Asian Journal of Water, Environment and Pollution*, Vol. 1, Nos 1/2, pp. 17–28, available at www.capitalpublishing.com/journal/; www.iospress.nl/html/09729860.html.

Haigh, M. J. In press. "Greening the curriculum: Appraising an international movement", *Journal of Geography in Higher Education*, Vol. 29, No. 1.

Haigh, M. J., L. Jansky, and J. Hellin. 2004. "Headwater deforestation: A challenge for environmental management", *Global Environmental Change: Human and Policy Dimensions*, Vol. 14, No. S1 (Special Issue – Focus on the International Year of Freshwater), pp. 51–61, available at www.elsevier.com/locate/gloencha.

Hellin, J. In press. *From Soil Conservation to Better Land Husbandry: Towards a Holistic Approach to Land Management*, Land Reconstruction and Management No. 4. Enfield, NH: Science Publishers.

Horn, R., J. J. H. van den Akker, and J. Arvidsson. 2000. "Subsoil compaction: Distribution, processes and consequences", *Advances in Geoecology*, Vol. 32, pp. 1–462.

IPCC. 1996. *Climate Change 1995 – Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC Secretariat.

Jackson, M. G. 1999. *Our Land, Our Life*, 7 vols. Almora, Uttarakhand: Paryavaran Shiksha Kendra.

Jansky, L., J. Krecek, and M. J. Haigh. 2003. *Sustainable Management of Headwater Resources* (Nairobi "Headwater" Declaration for the International Year of Freshwater 2003). Tokyo: United Nations University, Environment and Sustainable Development Programme, available at http://update.unu.edu/downloads/declaration.doc.

Joshi, S. P. and M. M. Srivastava. 1991. "The status of grazing lands of alpine regions in the Garhwal Himalayas", *Recent Researches in Ecology, Environment and Pollution*, Vol. 6, pp. 1–11.

Krecek, J. and M. J. Haigh (eds). In press. *Environmental Role of Headwater Wetlands.* Dordrecht: NATO/Kluwer.

Laszlo, E. 2002. *You Can Change the World: Action Handbook for the 21st Century – A Report from the Club of Budapest*. Clun: Postive News Publishing.

Macy, J. and M. Brown. 1998. *Coming Back to Life: Practices to Reconnect Our Lives, Our World*. Gabriola Island, BC: New Society.

Maltby, E. 1986. *Waterlogged Wealth: Why Waste The World's Wet Places?* London: Earthscan/IIED.

Mountain Agenda. 1998. *Mountains of the World: Water Towers for the 21st Century*. Berne: Mountain Agenda.

Naess, A. 1973. "The shallow and the deep, long range, ecology movement: A summary", *Inquiry*, Vol. 16, pp. 95–100 (reprinted in A. Drengson and Y. Inoue (eds). 1995. *The Deep Ecology Movement, An Introductory Anthology*. Berkeley, CA: North Atlantic Books).

Naess, A. 1987. "Self-realization: An ecological approach to being in the world", *Trumpeter*, Vol. 4, No. 3, pp. 128–131 (reprinted in A. Drengson and Y. Inoue (eds). 1995. *The Deep Ecology Movement, An Introductory Anthology*. Berkeley, CA: North Atlantic Books).

Newson. M. 1992. *Land, Water and Development: River Basin Systems and Their Sustainable Management*. London: Routledge.

Oldeman, L. R. 1994. "The global extent of soil degradation", in D. J. Greenwood and I. Szabolcs (eds) *Soil Resilience and Sustainable Land Use*. Wallingford: CAB International, pp. 99–118.

Oldeman, L. R., R. T. A. Hakkeling, and W. G. Sombroek. 1991. *World Map of the Status of Human Induced Land Degradation*. Wageningen: ISRIC/UNEP.

Paracchini, M. L. and J. V. Vogt. In press. "Mapping wetlands in European headwater areas", in J. Krecek and M. J. Haigh (eds) *Environmental Role of Headwater Wetlands*. Dordrecht: NATO/Kluwer.

Payutto, P. A. 1995. *Towards Sustainable Science: A Buddhist Look at Trends in Scientific Development*. Bangkok: Buddhadhamma Foundation.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. "Environmental and economic costs of soil erosion and conservation benefits", *Science*, Vol. 267, pp. 1117–1123.

Rajwar, G. S. (ed.). 1993. *Garhwal Himalaya: Ecology and Environment*. New Delhi: Ashish Publishing.

Ramsar Convention Bureau. 2000. *Wise Use of Wetlands*, Ramsar Handbook 1. Gland: Ramsar.

SAPA-AFP. 2005. "IOL environment: Countdown to environmental catastrophe", *Independent Online*, 24 January, available at www.iol.co.za/index.php?set_id=14&click_id=143&art_id=qw1106541006165B216; see also www.newscientist.com/channel/earth/climate-change.

Schneider, S. H. 1996. *Laboratory Earth: The Planetary Gamble We Can't Afford to Lose.* London: Weidenfield and Nicolson, Science Masters Series.

Shaxson, T. F. 1999. *New Concepts and Approaches to Land Management in the Tropics, with Emphasis on Steeplands*, FAO Soils Bulletin 75. Rome: FAO, Land and Water Development Division.

Shaxson, T. F., M. Tiffen, A. Wood, and C. Turton. 1997. *Better Land Husbandry: Re-thinking Approaches to Land Improvement and the Conservation of Water and Soil*, Natural Resource Perspectives No. 19. London: Overseas Development Institute, available at www.odi.org.uk/nrp/19.html.

Singh, J. S., U. Pandey, and A. K. Tiwari. 1984. "Man and forests: A central Himalayan case study", *Ambio*, Vol. 13, No. 2, pp. 80–87.

Soulsby, C., P. Rodgers, R. Smart, J. Dawson, and S. Dunn. 2003. "A tracer-based assessment of hydrological pathways at different spatial scales in a mesoscale Scottish catchment", *Hydrological Processes*, Vol. 17, No. 4, pp. 759–777.

Stocking, M. A. and N. Murnaghan. 2001. *Handbook for the Field Assessment of Land Degradation.* London: Earthscan.

UN. 2003. *Resolution 57/254. United Nations Decade of Education for Sustainable Development; Resolution Adopted by the General Assembly. United Nations General Assembly, 57th Session, 21 February 2003*, Agenda item 87(a) 02 55612, Document A/RES/57/254. New York: United Nations, available at www.unesco.ch/pdf/UNDekade.pdf.

Valdiya, K. S. 1985. "Accelerated erosion and landslide-prone areas in the central Himalayan region", in J. S. Singh (ed.) *Environmental Regeneration in Himalaya*. Nainital: Central Himalayan Environment Association, pp. 12–38.

Vivekananda. 1907. ‘‘Karma yoga’’, in *The Complete Works of Swami Vivekananda* 1, 1989 edn. Calcutta: Kolkata Advaita Ashrama, pp. 25–111.

Zlatic, M., S. Kostadinov, and N. Dragovic (eds). 2004. *Community-based Rehabilitation of Degraded Lands of Central Balkan Mountains and Northern Turkey*. Belgrade: Belgrade University Faculty of Forestry/UNU/WASWC/CEKOR.

Appendix

Nairobi "Headwater" Declaration for the International Year of Freshwater 2003

We, the participants in the International Conference on Sustainable Management of Headwater Resources, held in Nairobi (Kenya) on 5–8 September 2002,

1. Acknowledging with gratitude the United Nations General Assembly Resolution No. 55/196 to declare the year 2003 as the International Year of Freshwater, thus drawing the world's attention to the need to foster sustainable development and management of freshwaters;
2. Noting the outcome of the recent World Summit on Sustainable Development in Johannesburg 2002, where commitments were made "to increase access to clean water and proper sanitation, to increase access to energy services, to improve health conditions and agriculture, particularly in drylands, and to better protect the world's biodiversity and ecosystems";
3. Recognizing that headwater regions are sensitive environments, source areas for both surface and groundwater resources, and lands that affect the quality of freshwater supplies;
4. Keeping in mind that headwater regions lie at the margins of both watersheds and, often, social and economic systems;
5. Recognizing also the critical environmental functions of headwater regions and their importance for the livelihoods of both their inhabitants and for those who inhabit lands downstream as evoked in Chapter 18 *"Protection of the quality and supply of freshwater resources: application of integrated approaches to the development,*

management, and use of water resources" of Agenda 21 adapted at the United Nations Conference on Environment and Development (1992), and also as stipulated in its Chapter 13 entitled *"Managing fragile ecosystems: sustainable mountain development"*;

6. Affirming our concern to mitigate the consequences of the increasing human impact in headwater regions caused by competing demands for water, forestry, agriculture, energy production, tourism, transport and urban development, which continue to affect the environment adversely, not least with respect to the provision of clean water supplies and the maintenance of other hydrological functions;
7. Noting with further concern that policies can impair, seriously and inadvertently, the course of headwater resources management, and that this can create problems downstream for the quality, quantity and distribution of available freshwater resources;
8. Recognizing that sustainable management of headwater regions needs a holistic, integrated approach which respects the needs of all stakeholders in the regions, values and empowers the headwater inhabitants, and which recognizes their central role in the stewardship of headwater systems;
9. Affirming that the sensitive and scientific management of natural resources, supported by improved access to the high quality data required is essential for fostering development that is not only sustainable, but ideally self-sustaining;
10. Conscious that unsustainable management has negative impacts on the health, productivity, social and economic welfare and ecosystems of headwater regions;
11. Aware of the increasing demand for potable waters that will be required for human health, welfare and well-being, and of the crucial role that headwater regions will play in meeting this demand;
12. Conscious also of the potential negative interactions between the inhabitants of headwater regions and those downstream, including coastal areas, caused by competition for the limited resources available in the regions, and aware also that headwater areas accommodate and provide for livelihood of a large number of populations, whose activities and resources consumption may have significant effects on the well-being of those who live downstream;

Declare that:

13. Sustainable development should be the baseline for all environmental policy, planning, management practice, education and law in headwater regions;
14. UN agencies should continue their work with all stakeholders to appraise their situations, to identify gaps in knowledge, needs and constraints, and to support them in their efforts to resolve their problems

and undertake practical action towards more self-sustaining and environmentally sensitive development;

15. An ‘‘international commission’’ for headwater management should be established in order to provide direction and continuity for headwater issues and to create an awareness of headwater concerns at governmental level;
16. Priority should be given to the creation of new management structures at all levels, which should be designed to improve the coordination, cooperation and empowerment of all stakeholders of headwater regions, not least to enhance the participation of women, disadvantaged social groups and minority communities, and to tap and develop the full spectrum of local indigenous knowledge relating to watershed planning and management;
17. Greater effort should be devoted to the refinement of methods for generating and sharing the appropriate and reliable information needed for environmental research, planning and management and also for the transfer of appropriate low cost technologies, especially with respect to ‘‘cushioning’’ the impacts of environmental hazards for human populations;
18. Greater attention needs to be paid to the special roles and hydrological functions of headwater wetlands and peat lands, which should be a special focus for future headwater workshops, and also to the impacts of anthropogenic processes on watershed functions in headwater regions;
19. The quality of life for the inhabitants of headwater regions should become a primary concern, including the basic needs for a healthy environment and the regeneration of degraded headwater habitats where required;
20. Greater attention should be paid to applied environmental education aimed at building capacity for headwater management and changing social attitudes against wasteful and polluting uses of headwater resources;
21. NGOs (community-based non-governmental organizations devoted to environmental and/or social uplift) should be empowered to play a greater role in the planning, regeneration and management of headwater habitats, by promoting more efficient mechanisms for financial support for effective NGOs;
22. Greater attention should be given to management of headwaters in arid and semi-arid lands, especially with respect to groundwater management and improved accessibility of potable waters to headwater inhabitants, while the one of the main focuses should be to reduce the time wasted in carrying water to households from distant water sources;

23. Attention should also be paid to alternative measures that would reduce the dependence of downstream areas on the resources of headwater areas, including reducing wastage and increasing the efficiency of resource utilization, not least of water;
24. The equitable distribution and use of headwater resources remain a major concern, and planning and management of headwater regions needs to be integrated within the broader framework of watershed management that addresses the concerns of both headwater inhabitants and those downstream, including those living in coastal areas.

We therefore call upon UNU, UNESCO, UN-HABITAT, FAO, UNEP, UNDP and other concerned international and national organizations, governments of both developed and developing countries, corporations and NGOs, to facilitate headwater research, monitoring, capacity-building, self-sustaining sustainable development, and better management of the headwater environments, and to help create linkages and synergies in this regard among environmental managers, scientists, communities, policy/decision-makers, practitioners and the general public.

Acronyms

ASAL	arid and semi-arid land
AVHRR-NOAA	advanced very high resolution radiator – National Ocean and Atmosphere Administration
BLH	better land husbandry
BSD	Botanical Survey of India
CI	Channel Index
CIA	chemical index of alteration
cps	counts per second
CSI	Channel Sinuosity Index
DD	Forest Research Institute (India)
DEM	digital elevation model
ECHAM	European Centre for Medium Range Weather Forecasting model, Hamburg
ENSO	El Niño/Southern Oscillation
ESD	education for sustainable development
EWNRA	Ethio Wetlands and Natural Resources Association
EWRP	Ethiopian Wetlands Research Programme
FAO	UN Food and Agriculture Organization
FCC	false colour composite
FCCC	UN Framework Convention on Climate Change
FGD	focus group discussion
GCM	general circulation model
GEF	Global Environment Facility
GIS	geographical information system
GLASOD	Global Assessment of Soil Degradation
GPS	global/geographical positioning system

HCM	Headwater Control Movement
HIS	Hydraulic Sinuosity Index
IAEA	International Atomic Energy Authority
IAHC	International Association for Headwater Control
IFR	instream flow requirement
IK	indigenous knowledge
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
IWSC	IRC International Water and Sanitation Centre
KEFINCO	Kenya Finland Company
KWS	Kenya Wildlife Services
LARSIM	large area runoff simulation model
LSG	large-scale geostrophic
MRI	Mountain Research Initiative
MSL	mean stream length
NATO	North Atlantic Treaty Organization
NDVI	Normalized Digital Vegetation Index
NGO	non-governmental organization
NRIS	natural resources information system
O&M	operation and maintenance
PRA	participatory rural appraisal
PRSP	poverty reduction strategy paper
RGS	river gauging station
RSSP	Rural Sector Support Programme (Rwanda)
SLR	stream length ratio
SSI	Standard Sinuosity Index
SWC	soil and water conservation
TDS	total dissolved solids
TSI	Topographic Sinuosity Index
UNCED	UN Conference on Environment and Development
USGS	United States Geological Survey
USLE	universal soil loss equation
VI	Valley Index
WASWC	World Association of Soil and Water Conservation
WHO	World Health Organization
WMCC	wetland management coordinating committee (Ethiopia)
WOCAT	World Overview of Conservation Approaches and Technologies
WSSD	World Summit on Sustainable Development

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