In order to illustrate that environmental vulnerability involves a spectrum of threats, several specific examples are provided in this chapter. These examples demonstrate why it is so important to start with the assessment of vulnerability when studying the interaction of humans with the rest of the environment.

E.6.1 Population and Climate

Introduction

One aspect of the global change debate that has received relatively little attention from the Earth systems science community is the purposeful intervention of humans within the terrestrial hydrological cycle as we establish and use water resources. Recent studies have shown that this phenomenon is indeed global (Dynesius and Nilsson 1994; Vörösmarty et al. 1997; Postel et al. 1996) and the growth in water use by humans is likely to continue over the next several decades (Rijsberman 2000; United Nations 1997; Shiklomanov 1996). Water engineering will remain an important human endeavour over this time frame as both economic development and population growth will force future demands on the natural water system. The stabilisation of water supplies through control of terrestrial runoff and/or the translocation of water stocks from aquifers or through interbasin transfers will thus remain a fundamental feature of the land-based water cycle. These activities purposely seek to optimise water security and hence seek to reduce the degree of vulnerability to water shortages and/or excess.

In this contribution we document the emerging role of direct human usage of water. We explore the value of linking biophysical and socio-economic information within a common framework. We also highlight key areas of uncertainty and draw inferences about how our current knowledge base is related to the issue of water vulnerability. We summarise an emerging paradigm for successful water resources management and explain the role of the Earth systems science community in supporting this new strategy for water development.

Water Supply, Use and Emerging Patterns of Scarcity

Assessment of the global water supply has been an imprecise science. If we consider the renewable resource base to equal the long-term mean runoff we can find estimates which vary between 33,500 and 47,000 km³ yr⁻¹ (Kourzoun et al. 1978; L’vovich and White 1990; Gleick 2000; Shiklomanov 1996; Fekete et al. 1999). One of the most recent such assessments, made using time series of observed discharges over approximately 70% of the discharging land surface of the globe and a model-based extrapolation, offer 39,600 km³ yr⁻¹ (Fekete et al. 1999). A more classical accounting by Russian scientists cites 42,750 km³ yr⁻¹ (Shiklomanov 2000). Although one could view these differences as being of simple academic interest only, they become amplified at regional or smaller scales and can give substantially different views of per capita water supplies and hence vulnerability to water scarcity. For example, in North Africa the former study gives a total of 362 km³ yr⁻¹ while the latter shows 181 km³ yr⁻¹. Assuming a population in 1995 of 150 million we get per capita supplies varying between 1,200 and 2,400 m³ per capita. This estimate highlights the difficulty in attempting to assemble a coherent picture of water availability in the face of declining hydrographic monitoring (Vörösmarty et al. 2001). Further, in many parts of the world, groundwater is an important source of water supply (both renewable and non-renewable; Shiklomanov 1996). Our understanding of the hydrography of groundwater resources is even more limited, since well-logged, groundwater discharge/recharge, and aquifer property data are neither synthesised nor released to the global change community. Noteworthy exceptions exist for regional aquifers (e.g. High Plains in US; Weeks and Gutentag 1988; Nativ 1992), suggesting the feasibility of providing such information when suitable financial and technical resources are made available. Nonetheless, there is but one 1:10 M scale map (Dzhamalov...
and Zekster 1999) which is only now becoming available. High resolution global mapping of this important resource awaits further work and must be harmonised across the existing region-specific studies.

Larger uncertainties accompany aggregate levels of water use. Long term, there has been a more or less exponential rise in the withdrawal and consumption of water which supports human development (L'vovich 1990; Shiklomanov 2000). But significant uncertainties characterise the history of such studies. Recent reviews (Shiklomanov 1996; Gleick 2000) show that year 2000 water withdrawals as proposed in studies commencing in 1967 and ending in 1998 varied between 3,927 and 10,840 km³ yr⁻¹ with the extreme high value made in 1974. Even assessments made as late as 1987 show a relatively large range of estimates from 3,927 to 5,186 km³ yr⁻¹ for water withdrawals for year 2000. Country-level datasets (World Resources Institute 1996) for some countries are decades-old.

A prime example of such uncertainty is associated with the key component of water use globally, namely irrigation, which accounts for approximately 70% of contemporary withdrawals (Shiklomanov 2000). Irrigation area has been increasing steadily over the last several decades and it would be highly useful to have a systematic methodology to infer the land-area distribution, if not water use, by this water sector. The difficulty in assembling systematic data in part arises from the great diversity in how fresh water is obtained for farming, be it from groundwater resources in Arizona, from trapped or redirected local runoff in the rice paddies of SouthEast Asia, or from mainstream river water in the Nile floodplain or Columbia River valley. Figure E.11 shows a country-level accounting of irrigated land, contrasting reported statistics from FAO, the UN Food and Agriculture Organization, (World Resources Institute 1996; FAO 1998) with statistics derived from the 1-km land-cover dataset of the US Geological Survey’s Earth Resources Observation Systems Data Center (United States Geological Survey – EROS Data Center 1998) classified according to Olson (1994a,b). The disparity points to major uncertainties in our capacity to classify and inventory the area of irrigated lands. One important problem is that a standardised nomenclature is absent and “irrigated land” is interpreted differently across the globe (see also Froliking et al. 1999). In some cases, it is land that is potentially irrigable. In others, the term represents land that is now under irrigation or land that may have been retired from irrigation. The situation is further complicated when “irrigated land” represents an accounting of area multiplied by the number of crops grown each year (L’vovich 1990). A systematic nomenclature is clearly needed. A recent geo-referenced compilation (Döll and Siebert 2002) based on areas determined from maps generated primarily during the 1970s gives country-specific areas similar to FAO estimates for the mid-1990s, but the geographic updating has been optimised to match the national statistics.

Water scarcity has been defined in various ways, based on per capita supply, withdrawal-to-supply ratios, or coping ability (United Nations 1997; Falkenmark 1998). The inverse of per capita supply represents the water “crowding” and equals the number of people per flow unit. It has been postulated that a threshold of 1,000 people per 10³ m² yr of water supply is required for food self-sufficiency in the semi-arid tropics and sub-tropics (Falkenmark 1998). Although it can be argued that food self-sufficiency may not be an absolute necessity for the establishment of food security, it is standard policy in many countries as, for example, in India which has imported only a small fraction of its grain requirements for many years (FAO 1998). The level of economic development is important in coping with potential water stress. Thus, although southern Europe has a high level of relative water use (> 20% of supply), it is able to cope with such apparent scarcity. North Africa, on the other hand, is generally much less able to do so.

Global Assessment of Water Vulnerability: A Biophysical Approach

To make estimates of global water scarcity, we used a newly-developed runoff database developed at the University of New Hampshire, in collaboration with the WMO Global Runoff Data Centre (GDRC) in Koblenz, Germany (Fekete et al. 1999, 2002). The dataset provides spatially-distributed renewable water supplies at 30-minute (50 km) grid increments. The runoff database combines available discharge monitoring data with a water balance model driven by atmospheric variables such as air temperature and precipitation (Vörösmarty et al. 1997). A total of 663 discharge gauging stations,
which met strict selection criteria in terms of record length and consistency with neighbouring gauging stations, were selected from the GRDC archive for use in developing the database. These stations were co-registered to a 30-minute Simulated Topological Network (STN-30; Vörösmarty et al. 2000).

The Center for International Earth Science Information Network has produced a global population database using census data for 120,000 administrative units (CIESIN 2000). We compare conditions between 1995 and the year 2025, starting with a gridded dataset at 2.5-minute (4 km) grid increments. The 1995 cell counts were extrapolated exponentially to 2025 and then capped using the low growth projection for each country (United Nations Population Division 1998). The cell population counts were then aggregated to 30-minute grid increments to match the runoff database. Figure E.12 shows the population density in 1995. For this study, the low-growth projection is considered to be more realistic than either the medium or high projections (Seckler et al. 1999). But use of the low-growth projection, in conjunction with the maximum sustainable water supply, means that the water scarcity estimates should be considered as conservative. For the purposes of this study, we do not consider potential weather change impacts which add an additional layer of complexity and potential vulnerability. Future water scarcity may be more acute than this tabulation suggests.

The runoff and population databases were summed by river basin to calculate the renewable supply of water per person. We estimate scarcity using a set of standard rules (Hinrichsen et al. 1998). First, populations living in basins with water “crowding” of 590 to 1,000 people per \(10^6\) m\(^3\) yr of water supply are classified as water stressed, and tend to experience severe shortages in drought years. Second, people living in basins with 1,000–2,000 people per \(10^6\) m\(^3\) yr\(^{-1}\) are classified as water scarce, and can expect chronic shortages of freshwater that threaten food production and hinder economic development. Finally, people living in basins with more than 2,000 people per \(10^6\) m\(^3\) yr face absolute water scarcity, beyond which development is highly constrained without access to alternative water sources.

**River Basin Estimates**

Figure E.13 and Fig. E.14 show river basins under varying degrees of water stress in 1995 and 2025. (Only basins larger than 25,000 km\(^2\) are shown.) These maps show increased water scarcity in Southern and Eastern Africa, Pakistan and central Asia, but stable conditions in Latin America, South-east Asia, China and India. But this overview hides important basin-specific trends. Table E.1 shows total water supply, population, and water crowding in 1995 and 2025 for large basins that are currently water stressed or will be close to such stress by 2025. Together, they hold half the world’s population. Average water crowding in these basins is projected to increase by 25%, from 546 people per \(10^6\) m\(^3\) yr in 1995 to 735 people per \(10^6\) m\(^3\) yr by 2025. Water crowding in some basins, notably those in China, will increase by less than 15%, but the Indus and the Nile will suffer declines in excess of 40%. In the case of the Indus, this will result from the growth in Pakistan’s population, from 136 million in 1995 to 246 million in 2025. In the case of the Nile, the decline will mainly result from a doubling of Ethiopia’s population, from 55 million to 108 million. Egypt, the second most populous country in the basin, will see its population grow more slowly, from 52 million to 63 million.

**Global Estimates**

The river basin estimates were summed to give the total number of people living in conditions of water scar-
city in 1995 and 2025. Table E.2 shows that 2.3 billion people, or 41% of the world’s population, lived in conditions of water scarcity (> 590 people per 10^6 m^3 yr) in 1995, and 3.5 billion people, or 49% of the world’s population, will live in these conditions by 2025. The number of people facing conditions of absolute water scarcity (> 2000 people per 10^6 m^3 yr) will increase from 1.1 billion to 1.8 billion.

These results require two qualifications. First, they are only based on population growth (which decline in a few parts of the world). They do not take into account the effects on water supply of pollution, weather change, or impoundment. They therefore probably underestimate the actual decline in water supply per person. Second, because the analysis assumes a constant water demand per person, the results inevitably misrepresent water scarcity in certain basins.

**Effect of Tabulation Procedures and Their Contribution to Uncertainty**

The total number of people living in basins that have an annual renewable water supply of less than 1700 m^3 per person in 1995 is 60% higher than some previous estimates (e.g. Shiklomanov 1996). Although more current population data and a relatively low global runoff are contributing factors, the main reason is that this study estimated water scarcity using river basins rather than countries. Basin-level analyses capture more of the inherent spatial variability in population and runoff (and hence water scarcity) and therefore global estimates that aggregate basin-level results will tend to be more accurate than those based on country averages.
Using the methodology presented above, we can also show that on a per capita basis, global renewable freshwater supply will fall from 6,900 m$^3$ in 1995 to 4,500 m$^3$ in 2050. This is a large drop, but it must be recognised that the reduction is in reality highly region-specific. Indeed, it has been estimated that the bulk of the human population is in spatial and temporal proximity to only 30% of the renewable supply of freshwater (Postel et al. 1996) and that we use 50% of this supply. This is especially important in the world’s two most populous countries: China and India (Seckler 1999). Northern China is very dry, while southern China is very wet. Eastern India is very wet, while west and southern India are very dry. Because large numbers of people live in all these regions, aggregating them masks important within-country differences. Aggregate numbers thus underestimate the problem of potential water scarcity that is likely to be much more severe at more local scales.

To test this assertion, we tabulated relative water scarcity at four progressive levels of relative water use (i.e. total withdrawal/supply) using four different accounting units. We considered aggregations across 26 broad regions, all countries, drainage basins, and individual grid cells. Figure E.15 shows these results. First, our national level aggregation bears good resemblance to the work of Shiklomanov (1996) using his 26 composite regions. Our country-level aggregate also corresponds well at very low levels of water stress (< 0.1), although it differs substantially from the basin or grid accumulations. In turn, the basin aggregation differs substantially from the grid-based accounting at very low (< 0.1) levels of stress. In relative, but not absolute, terms it differs substantially from grids at moderate levels of stress. There is good correspondence between the basin-wide and grid-based estimates at high levels of stress. With an increasing number of accounting units ($10^1$--$10^5$ for regions-countries to $10^3$ for basins), we see an increased separation of the classes. In particular, there is a large reduction in the importance of the intermediate classes, which are an apparent by-product of a large spatial accumulation of information.
Although we can demonstrate sensitivity to the choice of accounting unit used, we cannot identify an optimal unit. This awaits further study by the water sciences community and a consideration of the broader issue of data availability and harmonisation across biophysical and socio-economic disciplines. The choice of accounting unit is important from the standpoint of determining the number of people at risk from water stress. In comparison to the regional or country-level tabulation which yields about 400 million under severe stress, the gridded or basin-level interpretation gives a substantially larger population, at about 2 billion. The conventional wisdom thus severely underestimates the degree to which the world's population is suffering from water scarcity.

Vulnerability and Essential Biophysical Data

The combination of biophysical and socio-economic datasets within a common geographic framework suggests that the world is a drier place than previously thought, and that population growth will result in a large and growing portion of the world's population living under conditions of water scarcity by 2025. The World Bank has long sought to help countries harness their water resources for economic development through its support to irrigation, water supply, sanitation, flood control, and hydropower. Water has been one of the most important areas of World Bank investment: between 1985 and 1998, it lent more than $33 billion, or 14% of project lending (World Bank 1998a).

But these projects have encountered serious implementation problems because they do not address the root causes of waste and mismanagement in the water sector. Several problems emerged. First, fragmented public investment programmes failed to optimise water allocation and emphasized supply development over demand management. Second, excessive reliance on overextended government agencies resulted in poor financial accountability and cost recovery. This led to a vicious circle of poor quality, unreliable service, low willingness to pay, inadequate operating funds, and further deterioration in service. Third, damage to freshwater ecosystems inherent in some projects was treated, if at all, by limited corrective actions and rarely by substantive adjustments to project design.

In response to these problems, the World Bank issued a water sector strategy in 1993 (World Bank 1993). The principal goal of the strategy was to improve water sector performance by ensuring the provision of water services in an economically viable and environmentally sustainable manner. The strategy recognised that to improve the performance of the water sector, it is necessary to help countries reform their water management institutions, policies, and planning systems. The strategy is being implemented through a new generation of water resources management projects. Noteworthy examples exist for Morocco and Mexico (World Bank 1996, 1998b).

To meet increased demand at reasonable cost, policymakers are exploring better ways to allocate existing water supplies and encourage users to conserve water. Better water management requires a significant improvement in the collection and analysis of hydrological data yet monitoring programmes in many countries have deteriorated sharply in recent years (Vörösmarty and Sahagian 2000). Paradoxically, at a time of growing water scarcity, we know less and less about the challenges and opportunities we face.

The constraints on hydrological monitoring are both financial and institutional. For example, both China and India have dense monitoring networks and tremendous analytical capacity but the effective use of these assets is not possible for several reasons. First, very few stations are linked by satellite or cell phone, resulting in lengthy delays as data are retrieved and transcribed by hand. Second, different agencies manage different gauges, often over different time periods, resulting in inconsistent data quality and fragmentary records. Third, hydrological data are not shared among agencies, let alone with the research community. Many data are considered state secrets. Fourth, limited data access is exacerbated by a move by many agencies toward full cost
recovery. Finally, because of the focus on flooding, hydrological models are often only calibrated using data collected during the rainy season. More accurate predictions would be possible if the models were calibrated using data collected throughout the year.

Hydrological monitoring capacity in many countries is deteriorating because of inadequate cost-recovery and reduced government support. The number of stations reporting to the Global Runoff Data Centre peaked in the mid-1980s and then fell sharply (Fekete et al. 1999). The decline has been most marked in Africa, where a recent analysis shows that the number of gauging stations in most countries is well below WMO guidelines (Rodda 1998). Although several international initiatives (e.g. W-HYCOS, GRDC) have sought to compile and publish atmospheric, oceanic, cryospheric and hydrological data, they ultimately depend on the quality of the national networks. Even in the United States the hydrological monitoring network has degraded. The USGS has been monitoring river flow and water quality for over 100 years. The network coverage expanded throughout the 1960s and 1970s but contracted sharply during the 1990s (United States Geological Survey 1999). More than 100 river gauges with long-term records, the single most important class of stations for environmental monitoring and design engineering, are being lost each year (Lanfear and Hirsch 2000). As a result, the network has become vulnerable as collaborating agencies have cut costs to meet their own specific needs, for example by only monitoring high or low flows, or by limiting public access.

Many countries reject the principle of free data access. Some industrialised countries have introduced legislation that would restrict the open access that the research community has traditionally enjoyed. In response, the International Union of Geodesy and Geophysics, the International Association of Hydrological Sciences, and the World Meteorological Organization have all passed resolutions calling for the free and unrestricted access to hydrological data (compare Sect. C.3.4). In less developed countries, data access is primarily limited by high prices, which are justified on the basis of recovering operating costs. As a result, fewer data are available to analysts and policy-makers in developing countries to design and implement the new policies they need to cope with water scarcity.

The Promise of New Technologies

Ideally, a hydrological monitoring system will generate a real-time, continuous stream of discharge measurements from selected locations in the river basin. In practice, this goal is not attained: stage, not discharge, is measured (discharge is inferred from stage using a set of empirical relationships, which must be recalibrated on a regular basis). Measurements are taken infrequently and irregularly, and the results are made available days or weeks after capture.

Advances in radar gauging, telemetry, the internet, and modelling can significantly improve monitoring performance. Satellite and cellular communications can transmit data in real-time from the gauging station to the internet. GIS-based hydrological models can integrate hydrological, meteorological, and elevation data to predict discharge and water quality across the river basin. For remote and inaccessible areas, Vörösmarty et al. (1999) propose the development of a hydrologically-oriented satellite to monitor river stage, surface velocity, and width. Using imaging radar and/or doppler lidar sensors, the satellite would measure the surface height of inland water bodies with an accuracy of 5–10 cm and river surface velocity with an accuracy of 20 cm per second, with a frequency of three to seven days. The data would be made freely available in near real-time to counteract the deterioration of terrestrial monitoring networks, data commercialisation, and long delays in processing and distribution. But however advanced the technology, an adequate ground network is still required to calibrate these remotely sensed measurements.

Conclusions

The future management of water must emphasize demand management, efficiency improvements and conservation. This requires increasingly sophisticated information on the functioning of the hydrological system and how it is affected by water management decisions. To this end, the Earth systems science community can provide valuable insight into an important component of the analysis, namely, a quantitative description of the terrestrial water cycle. The analysis presented here suggests that when socio-economic and biophysical datasets are linked in a relatively high resolution setting, we see an even more urgent picture of potential vulnerability in world water resources than previously acknowledged. The challenge will be to harmonise the information needs of the two communities, that is of the natural sciences and the social sciences. The Earth systems modelling community provides high-resolution datasets on water availability which transcend political boundaries, a reflection of the integrative nature of the water cycle. While our knowledge of water supply continues to require improvement, our knowledge of population distribution and water use statistics is arguably much more primitive. In many countries, there has been no census for over a decade and water use statistics for several countries are many years old. Investment in hydrological monitoring and analysis should be balanced
with increased support for socio-economic data collection. Socio-economists are well advised to adopt such a "boundary-free" perspective by standardising, both intra and internationally, the datasets necessary to quantify the drivers of water withdrawal and consumption. Finally, identification of water vulnerability will be based on vigilance and scientific hydrology. With international support, governments should seek to upgrade and extend their hydrological monitoring systems using the most cost-effective data collection, communication and analysis technologies available.

Fig. E.16.
The Lake Erhai basin

Acknowledgments

The authors would like to thank Uwe Deichmann (World Bank), who produced the population surfaces under contract to CIESIN and advised on the extrapolation of the data to 2025, and Greg Browder (World Bank), who provided the World Bank water sector project data and project papers. The authors would also like to acknowledge the contributions made by Richard Lammers (UNH) and Jose Simas, Danny Gunaratnam, and Nagaraja Rao.
Harshadeep (World Bank). The US Agency for International Development and the Dutch Ministry of Foreign Affairs provided funding for this paper.

Brad Bass Lei Liu Gordon H. Huang

E.6.2 Water Resources in the Lake Erhai Basin, China

Introduction

One of the most critical concerns facing both the national and local governments in China is the environmental degradation associated with rapid economic development. Chinese governments have been in the process of designing region-specific environmental regulations, but the decision-making process requires a sound understanding of the significant drivers of regional environmental problems and the effects of policy changes on different sectors and decision variables. One sector that has drawn considerable interest is water resources; in particular, the impact of economic development on water resources and how these impacts are modified by other factors such as climatic variation and change.

The Lake Erhai basin provides an illustration of the integrated impacts of several factors, including weather, on water resources. The basin is host to agricultural and industrial production, a net-cage fishery, forestry and tourism, but its water resources are also required for municipal water and navigation. The rapid economic development and population growth of recent years has been accompanied by increased amounts of water pollution due to industrial wastewater emission, eutrophication in Lake Erhai due to nutrients from runoff and the fishery, and soil erosion due to deforestation. In order to address these concerns, a research project entitled “Integrated Environmental Planning for Sustainable Development in the Lake Erhai basin” was undertaken between 1996–1998 with support from the United Nations Environmental Programme.

The Lake Erhai basin is located at 25°25’-26°10’ N and 99°32’-100°27’ E and covers an area of 2,565 km² within the jurisdiction of Yunan Bai National Autonomous Prefecture, China (Fig. E.16). Lake Erhai has an approximate area of 250 km², an average depth of 10.2 m and a storage volume of 28.2 x 10⁶ m³. There are 117 rivers and streams that drain into Lake Erhai, mostly from the north through several smaller lakes and which drain into the Mizo, Luoshijiang and the Yunganjiang Rivers from the east. The Xier River is the only river flowing out of the lake and is the river most affected by industrial discharge. The basin also includes mountains, hills and alluvial plains. Land use includes forest (44.7%), grassland (20.3%), farmland (14.5%), human habitat (2.7%), abandoned land (1.7%), transportation (0.5%), and water bodies occupy 9.5% of the basin.

The vulnerability assessment diagram has been modified for this region and expanded to eight subsystems - population, agriculture, industry, tourism, water resources, pollution control, water quality and forestry - and their interrelations (Fig. E.17). For example, industrial development brings economic benefits but also consumes raw materials from forestry and agriculture and discharges wastewater into the Xier River. A system dynamics (SD) approach was used to model the interactions between the various components in the Lake Erhai basin. The relationships were quantified using Professional Dynamo Plus.

The governments that are involved want to consider how limits to economic development would impact on water quality and quantity, the sensitivity of these impacts to variations in weather and then determine an appropriate economic development policy. A vulnerability assessment was used to assess the impact of four different economic development policies on the available water resources in the Lake Erhai basin and the impact of variable precipitation. The results indicated that continued high levels of economic development carry the greatest risks to water quality, runoff from agriculture would become more of a threat under higher levels of precipitation, and a reduction in precipitation could lead to higher levels of eutrophication. However, the high levels of uncertainty in some key variables will increase the difficulty of justifying any particular planning alternative.

Verification and Sensitivity Analysis

The ErhaiSD model was verified using data from 1990-1994 for 14 variables. While the errors for most variables are quite low, the discrepancies between actual and simulated total industrial output are as high as 18% in one year and for industrial COD (Chemical Oxygen Demand) discharge the discrepancies were as high as 40% in 1994. These errors could be attributable to a number of factors. Important relationships may be missing from the model, or the relative weights of different relationships may be incorrect. A sensitivity analysis was used to examine the contributions of the model’s parameters.

A concept of sensitivity is defined as follows:

\[
S_Q = \frac{\Delta Q(t)}{Q(t)} \frac{\Delta X(t)}{X(t)}
\]

(E.7)

where \( t \) is time, \( Q(t) \) denotes the state at time \( t \), \( X(t) \) represents the parameter, \( S_Q \) is the sensitivity of \( Q \) to \( X \), and \( \Delta Q(t) \) and \( \Delta X(t) \) represent the increments in \( Q \) and \( X \) at time \( t \).

In assessing the sensitivity, 19 variables and 27 parameters were analysed. Each parameter was increased and decreased by 10% every four years from 1994 to 2010. The model was relatively invariant to these changes except for industrial COD discharge (ICODT) which was very
sensitive to several population parameters. To assess the seriousness of the problems with ICODT, planners, policy-makers and industrial stakeholders must agree on an acceptable uncertainty for this variable. If the model uncertainty is much higher than the acceptable uncertainty, then this decision variable should only be used in a restricted manner (ICODT increases or decreases relative to the previous time step) or not be used at all.

Vulnerability Assessment

The ErhaiSD model was run for a period of 15 years with 1996 identified as the year for generating alternative scenarios. The simulation exercise included a base run (BR) and three alternative scenarios (A1–A3), provided by local authorities based on a previous planning study (Wu et al. 1997), balancing economic and environmental objectives (1), emphasising industrial growth (2) and emphasising increasing water pollution control. The results are presented for gross industrial output (PIOT), industrial wastewater generation (ISWT), industrial COD emission and water pollution index (Fig. E.18a–d). The model suggests that water pollution will be reduced in all three alternatives. Alternative 2 will result in marginally higher amounts of economic growth than Alternative 1, yet with much larger amounts of industrial discharge. The COD concentrations could be reduced by...
Fig. E.18. Simulation results of the ErhaiSD model with a base run (BR) and three alternative scenarios (A1–A3). a Gross industrial output values; b total industrial wastewater generation; c total industrial COD emissions; d water pollution index.

50% through the development of regional wastewater treatment systems; the best improvement occurs in Alternative 3 due to the lower amounts of COD discharge. Alternatives 1 and 3 produce substantially lower amounts of industrial discharge, but control of this variable is not sufficient as all of the alternatives contribute a similar amount of total dissolved N and P. Although Alternative 3 emphasizes agriculture, the amounts of total dissolved N and P in the back-flowing irrigation water (NAWUR and PAWUR) were only marginally higher than Alternatives 1 and 2.

Vulnerability to Weather

In addition to the direct discharge of industrial waste and nutrients, water quality is closely related to precipitation and runoff. To assess the vulnerability of the basin to seasonal weather variability – and perhaps climate change – three precipitation scenarios were considered, corresponding to dry, average and wet seasons in the region. Table E.3a–c present the impacts of the three precipitation scenarios on the Xier River, for the three planning alternatives, before and after the installation of wastewater treatment. The COD concentration is highest under the dry scenario, even with treatment facilities. An additional simulation was conducted using the three precipitation scenarios under the assumption of increasing forest coverage. The results are presented for Alternative 1 only, as the impacts were similar across all three alternative futures (Table E.4a–c). Under the wet scenario, the N and P loadings are increased due to increased surface runoff, soil erosion and in-lake turbulence. In the dry scenario the N and P loadings are much lower. However, eutrophication could still be a problem due to intense sunlight and higher temperatures as occurred in August and September of 1996, for example, when the algae count and the COD reached their highest levels in ten years, most likely due to strong thermal stratification and weak dispersion.

Conclusion

The Lake Erhai basin’s water supplies are vulnerable to a wide range of factors including the weather. The ErhaiSD model suggests that choosing an alternative management procedure, which balanced industrial growth with environmental concerns or one that favours agriculture, could reduce industrial discharge. This is particularly important under a scenario of reduced precipitation, as the COD levels are inversely proportional to water quantity. All of the planning alternatives were similar in terms of total dissolved N and P, but this could be reduced through increasing the forest coverage. The model suggested that N and P levels were proportional to water quantity, but it did not reflect the potential for eutrophication under a scenario of reduced precipitation. These results are problematic for planners in that any precipitation scenario that deviates from average conditions will worsen water quality. The industrial discharge would have to be controlled through additional wastewater treatment and/or reduced industrial growth. If the future weather were to favour a drier precipitation regime, the region’s development plan could be altered to
allow for more industrial growth, although it should be noted that industry requires significant amounts of water that might not be readily available. However, the amount of industrial discharge is the one variable that is highly uncertain in ErhaiSD. Without knowing the acceptable level of uncertainty, it is difficult to use the model as the sole basis for controlling industrial discharge. Because of the high degree of uncertainty there are risks in accepting the model as a basis for controlling industrial discharge. This case study did not explicitly account for climatic uncertainties in the decision, an analysis which is presented in Bass et al. (1997).

Table E.3. COD (Chemical Oxygen Demand) concentration in the Xier River before and after wastewater treatment processes

<table>
<thead>
<tr>
<th>Alternative 1</th>
<th>Alternative 2</th>
<th>Alternative 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>before/after</td>
<td>before/after</td>
<td>before/after</td>
</tr>
<tr>
<td>a Average season</td>
<td>before/after</td>
<td>before/after</td>
</tr>
<tr>
<td>1998</td>
<td>73.02</td>
<td>63.14</td>
</tr>
<tr>
<td>2001</td>
<td>76.24</td>
<td>59.17</td>
</tr>
<tr>
<td>2004</td>
<td>81</td>
<td>56.9</td>
</tr>
<tr>
<td>2007</td>
<td>87.66</td>
<td>56.21</td>
</tr>
<tr>
<td>2010</td>
<td>91.89</td>
<td>55.1</td>
</tr>
<tr>
<td>b Dry season</td>
<td>before/after</td>
<td>before/after</td>
</tr>
<tr>
<td>1998</td>
<td>97.16</td>
<td>83.63</td>
</tr>
<tr>
<td>2001</td>
<td>101.59</td>
<td>78.16</td>
</tr>
<tr>
<td>2004</td>
<td>108.04</td>
<td>74.91</td>
</tr>
<tr>
<td>2007</td>
<td>117.18</td>
<td>73.80</td>
</tr>
<tr>
<td>2010</td>
<td>123.09</td>
<td>72.25</td>
</tr>
<tr>
<td>c Wet season</td>
<td>before/after</td>
<td>before/after</td>
</tr>
<tr>
<td>1998</td>
<td>61.68</td>
<td>53.49</td>
</tr>
<tr>
<td>2001</td>
<td>64.39</td>
<td>50.26</td>
</tr>
<tr>
<td>2004</td>
<td>68.37</td>
<td>48.44</td>
</tr>
<tr>
<td>2007</td>
<td>73.94</td>
<td>47.80</td>
</tr>
<tr>
<td>2010</td>
<td>77.43</td>
<td>47.08</td>
</tr>
</tbody>
</table>

Table E.4. Simulation results for Alternative 1 for normal, dry and wet season

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest coverage (FCR) (%)</td>
<td>44.7</td>
<td>50.5</td>
<td>56.2</td>
<td>62.0</td>
<td>67.7</td>
</tr>
<tr>
<td>N concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.31</td>
<td>0.30</td>
<td>0.28</td>
<td>0.27</td>
<td>0.25</td>
</tr>
<tr>
<td>P concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.0272</td>
<td>0.0265</td>
<td>0.0254</td>
<td>0.0251</td>
<td>0.0241</td>
</tr>
<tr>
<td>b Dry season</td>
<td>44.7</td>
<td>50.5</td>
<td>56.2</td>
<td>62.0</td>
<td>67.8</td>
</tr>
<tr>
<td>C concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.28</td>
<td>0.27</td>
<td>0.26</td>
<td>0.24</td>
<td>0.23</td>
</tr>
<tr>
<td>P concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.026</td>
<td>0.0255</td>
<td>0.0245</td>
<td>0.0244</td>
<td>0.0235</td>
</tr>
<tr>
<td>c Wet season</td>
<td>44.7</td>
<td>50.5</td>
<td>56.2</td>
<td>62.0</td>
<td>67.7</td>
</tr>
<tr>
<td>N concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.32</td>
<td>0.31</td>
<td>0.29</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>P concentration in Lake Erhai (mg I⁻¹)</td>
<td>0.0279</td>
<td>0.0272</td>
<td>0.026</td>
<td>0.0256</td>
<td>0.0245</td>
</tr>
</tbody>
</table>

Changming Liu

E.6.3 Yellow River: Recent Trends

Physical and Hydrological Characteristics

The Yellow River, or Huang He, the second largest river in China, is known for its high silt content. It originates from the Yueguzonglie basin, being about 4,700 m in elevation on the north side of the Bayankala Mountain in the Qinghai-Tibet Plateau. It flows across nine provinces from west to east and, finally, it enters the Bo Sea.
the Yellow Sea) at Kenli County, Shandong province. It lies between 96 to 119° E and 32 to 42° N, with a drainage area of 752,000 km² and a main course length of 5,464 km. Most of the Yellow River area is arid or semi-arid (Liu and Liang 1989). The area of its drainage basin accounts for 8% of the national area while the runoff makes up only 2% of the national total.

The Yellow River is the most important water source of north-west and north China. It serves as the water supply for a population of 144 million, 16 Mha cropland, 50 large or middle sized cities, and as the energy base of Inner Mongolia, Shanxi, Shaanxi, and the Zhongyuan and Shengli oil fields. The upper and middle stream of the Yellow River covers an area of 730,000 km², which accounts for 97% of its total drainage area (Liu and Li 2000). Most of this area consists of mountains and high plateaus. The lower stream is quite flat with a length of 780 km flowing across the North China Plain.

Figure E.19 gives an overview of the Yellow River with its three sub-basins, e.g. upper, middle and lower reach.

The annual average runoff of the Yellow River is 58.0 billion m³ based on 56 years of data. The area above Lanzhou accounts for 55.6% of the total runoff of the river (Liu and Li 2000). The runoff changes greatly in different years and is distributed unevenly within a year. About 70% of the total runoff results from the rainy season (from June to September).

The prominent characteristic of the Yellow River is “short of water and rich in sediment load”. The silt content of the Yellow River ranks the first among China’s rivers (Liu and Liang 1989). The average annual sediment discharge (Table E.5) is 1.6 billion tons (taking the Samenxia station as representative), the average silt content is 35 kg m⁻³, the maximum sediment discharge is 3.92 billion tons per year (1933) and the maximum silt content reached 920 kg m⁻³. The sediment discharge during the flood season (July to October) provides 90% of the annual amount. The yearly fluctuation of sediment discharge is quite high. The sediment discharge in a high precipitation year is twice the average. The maximum and minimum sediment discharge ratio can reach even higher values. For example, the sediment discharge in 1933 was 3.92 billion tons, which was 8.2 times that of 1928 (0.48 billion t yr⁻¹). The hyperconcentrated sediment load in the Yellow River has resulted from environmental problems such as severe soil erosion in the Loess Plateau (Liu 1981; Liu and Liang 1989).

**Change in Water Quality Indicators**

The runoff of the Yellow River is decreasing which reduces the capacity of the river to cleanse itself by flushing. At the same time, pollution control of the Yellow River has lagged. Since there are no complete laws for water resource protection and a united management mechanism, the water use and sewage discharge increases have resulted in increased pollution load year

---

**Table E.5. The yearly characteristic data of the Yellow River basin**

<table>
<thead>
<tr>
<th>River course</th>
<th>Catchment area (10³ km²)</th>
<th>Length of river course (km)</th>
<th>Natural runoff (10⁶ m³)</th>
<th>Sediment discharge (10⁶ t)</th>
<th>Precipitation (mm)</th>
<th>Average temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper reach</td>
<td>38.6</td>
<td>3471.6</td>
<td>312.6</td>
<td>1.42</td>
<td>401.6</td>
<td>3.22</td>
</tr>
<tr>
<td>Middle reach</td>
<td>34.4</td>
<td>1206.4</td>
<td>246.6</td>
<td>14.9</td>
<td>546.2</td>
<td>9.22</td>
</tr>
<tr>
<td>Down reach</td>
<td>2.2</td>
<td>785.6</td>
<td>21.0</td>
<td>0</td>
<td>675.3</td>
<td>14.46</td>
</tr>
<tr>
<td>Total</td>
<td>75.2</td>
<td>5463.6</td>
<td>580.2</td>
<td>16</td>
<td>475.9</td>
<td>9.22</td>
</tr>
</tbody>
</table>
by year. The pollution of the Yellow River has become worse which has been attributed to different reasons with mining one of the main sources (Ongley 2000).

In Summer 1998, a water quality assessment was performed, based on monitoring data of 69 segments (26 of mainstream, 43 of tributaries) with a total length of 7,158 km in the Yellow River basin. The result illustrates the water problem of the Yellow River, i.e. reflects the serious degradation of the extensively used waters: grade1 I–III made up only 26.1%, grade IV made up 38.6%, grade V made up 13.0% of the total length. The most seriously polluted water is unsuitable for any use, and does not even get a grade as it is inferior to grade V. 22.3% of the total length belonged to this category, that is below grade V. This means of the total length of the river with polluted water, i.e. belonging to grade IV, V and even worse than V, was 73.9% of the total length assessed in June to September 1998. Comparing the water quality of 1998 with that of 1985, the length of river with water quality worse than grade III has increased by 58.8%.

The long periods of low flow and drying-up in the lower reach of the Yellow River have led the wetland areas in the delta to decrease. The groundwater table has declined without enough fresh water recharge and the salinisation area has increased. The water environment of the wetland has changed and threatened the life of hundreds of wild plants and 180 kinds of birds. It is damaging the biological diversity of the delta.

Table E.6. Statistical data of sediment yields after Chen et al. (1998) (empty spaces in the table are unmeasured values)

<table>
<thead>
<tr>
<th>River or reach</th>
<th>Catchment area (10^3 km²)</th>
<th>Serious soil erosion area (10^3 km²)</th>
<th>Annual average sediment discharge (10^6 t)</th>
<th>Silt content (kg m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flood</td>
<td>Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High sediment yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hekouhen to Loumen</td>
<td>11.16</td>
<td>7.57</td>
<td>9.73</td>
<td>274</td>
</tr>
<tr>
<td>Above Jiaokouhe of Beluole</td>
<td>1.72</td>
<td>0.66</td>
<td>1.0</td>
<td>492</td>
</tr>
<tr>
<td>Above Tingkou of Jinghe</td>
<td>3.47</td>
<td>2.95</td>
<td>2.64</td>
<td>485</td>
</tr>
<tr>
<td>Above Nanhechuan of Weihe</td>
<td>2.34</td>
<td>1.75</td>
<td>1.64</td>
<td>248</td>
</tr>
<tr>
<td>Sub total</td>
<td>18.69</td>
<td>12.93</td>
<td>15.0</td>
<td>301</td>
</tr>
<tr>
<td>Low sediment yield</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above Lanzhou of Yellow River</td>
<td>22.3</td>
<td>1.32</td>
<td>4.11</td>
<td></td>
</tr>
<tr>
<td>Lanzhou to Hekou</td>
<td>16.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above Hejin of Fenhe</td>
<td>3.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below Nanhechuan of Weihe</td>
<td>4.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above Wuhe of Qinhe</td>
<td>1.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Above Heshigan of Yi-Luote</td>
<td>1.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below Loumen</td>
<td>3.86</td>
<td></td>
<td></td>
<td>-0.73 (sifting)</td>
</tr>
<tr>
<td>Sub total</td>
<td>54.3</td>
<td></td>
<td></td>
<td>5.24</td>
</tr>
<tr>
<td>Total</td>
<td>73.0</td>
<td>17.0</td>
<td>35.6</td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgement

This chapter was supported by the Chinese Key Project: G19990436-01.

Roland E. Schulze

E.6.4 Examples of Hazard Determination and Risk Mitigation from South Africa

The Approach, the Hydrological Model and the Spatial Databases Used

This section illustrates some of the concepts of risk, hazard and vulnerability within a context of hydrological risk management as described in Chapt. E.5, using examples from South Africa, defined here as the contiguous area of 1,267,681 km² made up of the nine provinces of the Republic of South Africa plus the landlocked Kingdoms of Lesotho and Swaziland. The country/regional scale is chosen to identify regions of similar hydrological hazard levels and thereby to distinguish between areas of higher and lower potential hydrological risk. Such a comparative view is important from the perspective that risk management is a national/regional responsibility and that this analysis may assist in identifying target areas for potential priority attention. Many of the hazard/risk indices presented by way of maps are in the form of ratios, rather than as absolute values, to highlight sensitive areas on a relative scale.

---

1 In China, the water quality is classified in five grades, in descending order from the highest quality (I) to the poorest one (V).
A regional analysis requires a hydrological model to be operated with suitable hydrological spatial databases. The hydrological model selected was the ACRU agrohydrological modelling system (Schulze 1995, and see Sect. D.2.6.6.2), developed in South Africa for catchment scale simulation of runoff components, sediment yield, reservoir yield, irrigation supply/demand and crop yield analysis, and containing routines for the assessment of land use/management as well as climate impacts on hydrology. ACRU is a widely verified physical-conceptual and daily time step simulator operating on a multi-layer soil water budget described in detail in Schulze (1995). The ACRU model has been widely verified at catchment scale, both in South Africa under a range of hydroclimatic and physiographic conditions (e.g. Schulze 1995) and elsewhere (e.g. in the USA, in Germany and Zimbabwe).

For the production of South Africa scale maps shown in this chapter, quality controlled daily rainfall for the concurrent 44-year period 1950–1993 was input for each of the 1946 Quaternary catchments which have been delineated for South Africa, Lesotho and Swaziland. For each Quaternary catchment other atmospheric parameters (e.g. daily maximum and minimum temperatures; A-pan equivalent reference potential evaporation) were also input, as were hydrological soil parameters. For purposes of producing comparative hydrological hazard maps, land cover was assumed to be grassland in fair hydrological condition (i.e. 50–75% cover).

**Examples of General Hydrological Hazard Indices**

To set the scene, Fig. E.20 (top) shows mean annual precipitation (mm), which characterises the long-term quantity of available water to a region, to display a general westward decrease, with relatively low mean annual precipitation – a first indication of a largely semi-arid climate and potentially high risk natural environment. A simple aridity index expressed as the ratio of mean annual potential evaporation to mean annual precipitation (Fig. E.20, middle) emphasizes the hazard of hydrological semi-aridity, because it amplifies the effects of a low mean annual precipitation when that is evaluated in association with the region’s high atmospheric demand. The aridity index is an already high 2–3 where mean annual precipitation is 600 mm, increasing to >10 and even >20 in the west. A consequence largely of the high aridity index is that the conversion ratios of rainfall to runoff over most of South Africa are exceptionally low (Fig. E.20, bottom) with, overall, only 9% of rainfall manifesting itself as runoff. These low runoff ratios, simulated with the ACRU model (Schulze 1995), result in a high hydrological vulnerability over much of the region.

**Example of a “Deprivation” Event, Hydrological Uncertainty and of Variable Sensitivity: The 1982/3 El Niño event over South Africa**

The 1982/1983 El Niño was one of the most severe experienced over South Africa. The manner in which such an event impacts on different hydrological responses is illustrated in Fig. E.21. Observed rainfall and simulated runoff and recharge into the groundwater zone through the soil profile are all expressed as ratios of their respective long-term (1950–1993) median values. For much of the region the El Niño season’s rainfall was 60–75% of the median, however, with sizeable areas receiving within the range of expected rainfalls (i.e. 75–125%) while some others received only 20–60% of the norm (Fig. E.21, top). The corresponding runoff responses display much more complex patterns spatially and in the range of ratios. Much of the region yielded only 20–60% of the long-term runoff (Fig. E.21, middle), with considerable areas generating <20% of the expected runoffs. This shows clearly once more the intensifying effects of the hydrological cycle on rainfall perturbations, as well as the dependence of hydrological responses not only on total rainfall amounts, but also on individual events, rainfall sequences and antecedent catchment wetness conditions, i.e. on the hydrological uncertainty created by meteorological and catchment conditions.

Some hydrological processes and responses display higher sensitivities, and thus higher potential vulnerabilities, than others. This is illustrated by the recharge to groundwater during this El Niño event, which was impacted even more severely than runoff (Fig. E.21, bottom). Generally only 0–20% of the expected recharge was simulated to take place, the reason being that a higher threshold has to be reached for recharge to commence than for stormflow to start occurring.

**Example of an “Assault” Event as an Index of Potential Vulnerability and Stochasticity by Quantitatively Defined Endpoints in Regard to Depth, Duration, Frequency and Area Affected**

Episodic flood generating events display considerable stochasticity (i.e. unknowable randomness). As an index of potential vulnerability, the flood hazard example presented below as an “assault” event illustrates the relative spatial differences over South Africa between the severity of the 1:50 year 1-day flood-producing rainfall, and consequent runoff, compared with what could be considered the annual expected 1-day values, i.e. the 1:2 year event. Ratios of 1:50 to 1:2 year rainfalls are generally between 2 and 4 (Fig. E.22, top), with lower ratios
Fig. E.20.
Indices of South Africa's largely semi-arid hydrological environment: (top) Mean annual precipitation (mm), (middle) aridity index expressed as the ratio of mean annual potential evaporation to precipitation and (bottom) the conversion ratio of mean annual runoff to rainfall (from Schulze 1997a).
Fig. E.21. Indices of hydrological amplifications of climate fluctuations: Ratios of the 1982/1983 hydrological year's rainfall (top), simulated runoff (middle) and recharge to groundwater (bottom) to long-term median values (after Schulte 1997a,b).
over central areas, but increasing to 10 in parts of the drier west. These rainfall ratios, however, manifest themselves as 1-day flood depths 4–10 times higher in the eastern areas of South Africa, and up to 50 times and higher over significant tracts of the drier west (Fig. E.22, bottom). While floods may be an infrequent occurrence in the west, this example illustrates that rare floods have the potential to do severe damage because of their unexpectedly high relative magnitudes.

**Example of Uncertainty through Use of Short Datasets**

Statistical hazard determination is frequently fraught with uncertainties as a consequence of using short datasets to determine high recurrence interval values of design rainfall or runoff. To illustrate this for hydrological design purposes, the 1:50 year 1-day rainfall and runoff estimated for a short 22-year period 1972–1993 was plotted as a ratio against 1:50 year 1-day rainfall and runoff estimated for double the period, i.e. the 44 years 1950–1993. In each case the log normal extreme value distribution was applied to the annual maximum series, in the case of runoff generated with the ACRU model. If the short records were representative of the expected population of the annual maximum series, the ratio would be around 1.

Figure E.23 shows this clearly not to be the case. Large tracts of South Africa display rainfall ratios between 0.75 and 0.95 and even < 0.75, while other areas show ratios in excess of 1.25 (and even 1.50). Estimating design rainfalls from short record lengths may thus result in severe underestimations or overestimations, with these errors amplified once design runoff is estimated from the rain-
Examples of Hazard Determination and Risk Mitigation from South Africa

Fig. E.23.
Ratios of “short” (1972–1993) to “longer” (1950–1993) design rainfall and runoff in South Africa for the 50-year return period 1-day event (from Schulze 2001)

Much of South Africa’s natural grassland (veld) has recently been shown to be heavily over-utilised (Hoffman et al. 1999). Hydrologically, the degradation through overgrazing of veld from good to poor condition, with its reduction in vegetal cover from >75% to <50%, implies enhanced stormflows through reduced interception, evaporation and transpiration potentials as well as infiltrability, shortened catchment lag times which increased peak discharges and greater exposure to soil erodibility through removal of mulch and shorter drop fall heights. These variables were changed for each of the 1946 Quaternary catchments covering South Africa in ACRU model simulations of stormflows, peak discharges and sediment yield to reflect veld in good v. poor management condition. Figure E.24 (top) shows that annual stormflows from veld in degraded condition are generally 1.5–2.5 times as high as those from good condition.

Example of Secondary Hazard Modification Through Land-use Practices: The Case of Grazing Management

Land-use practices have already been shown to play a significant role in long-term average hydrological responses (cf. Mgeni Case Study, Chapt. D.7), but perhaps even more dramatically so at the extremities of frequency distributions (e.g. Schulze 1989, 2000). An example of secondary hazard modification by manipulating land-management practices is given below.

fall (Fig. E.23, bottom). The importance of record length can therefore not be overemphasized, particularly in light of the worldwide trend, certainly in developing countries and evident also in South Africa, of declining hydrometeorological recording networks.
Fig. E.24. Ratios of annual stormflows (top) and sediment yields (bottom) in South Africa from veld in poor vs. good hydrological condition (from Schulze 2001).

Fig. E.25. Example of simple benefit analysis of seasonal runoff forecasts over South Africa (after Schulze et al. 1998).
Fig. E.26. Schematic illustration of the reduction of uncertainty in a reservoir operation through application of forecasting techniques

Veld under good management. When converted to sediment yields, however, the factor difference becomes 2.5–7.5 times, and even >7.5 times (Fig. E.24, bottom), clearly illustrating how a hazard, in this case stormflow and especially sediment yield, can be modified positively by good grazing management and/or rehabilitation of overgrazed lands.

Example of Vulnerability Modification through Seasonal Forecasting of Runoff

Vulnerability modification is a form of risk mitigation which includes, inter alia, assessing the benefits of forecasting streamflows for the rainy season ahead. Statistically derived categorical seasonal rainfall forecasts four months ahead are made for eight regions of South Africa by the South African Weather Service, for three categories, i.e. “above average”, “near average” and “below average” seasonal rainfalls. If seasonal rainfall forecasts were a random process, such three-category forecasts would be correct 33% of the time. If seasonal categorical rainfall forecasts are “translated” into seasonal runoff forecasts, these could become very valuable reservoir operations and irrigation application planning tools for water resources managers. Seasonal categorical rainfall forecasts for the eight forecast regions in South Africa were downscaled to daily rainfall values using techniques described in Schulze et al. (1998b) for application with the ACRU modelling system to over 1500 Quaternary catchments in South Africa. A simple benefit analysis of forecasting skill was undertaken, in which a “win” was recorded if, for the historical seasonal rainfall forecast, the simulated seasonal runoff was closer to the runoff simulated with actual historical rainfall than the median seasonal runoff, while a “loss” was recorded when median runoff was closer to the actual than the forecast runoff. “No difference” implies forecasted and median runoffs within 5% of one another. Figure E.25 illustrates that, when excluding three seasons out of 15 for which the rainfall forecast accuracy proved 100% wrong, i.e. 1981/1982, 1987/1988 and 1990/1991, most of southern Africa scores more “wins” than “losses”. The impacts of short term climate perturbations such as the El Niño phenomenon have already been illustrated. This forecast analysis indicates that even at the current level of seasonal forecast accuracy (around 62% if the 3 worst forecasts in 15 are omitted) these can potentially be “translated” into an operational tool for water resources managers which could prove statistically more accurate than the current practice of forecasting based on historical expected, i.e. median, runoffs with wide uncertainty bands, as shown in Fig. E.26.

Are Certain Areas in South Africa Hydrologically More Sensitive than Others to the Individual Forcing Variables of Climate Change?

Figure E.27 illustrates the relative sensitivities on mean annual runoff of ΔT (assumed to be a uniform increase of 2 °C over southern Africa) and ΔP (changed through −10% to +10% of the present). In each case the other two variables are held constant at present levels when running the daily ACRU model. The hydrological system is relatively insensitive to temperature changes that affect evaporation and hence runoff. The increase of 2 °C reduces mean annual runoff over most of summer rainfall areas in South Africa by only 5% (Fig. E.27, top). However, in the south-west winter rainfall region, the response to temperature becomes more dramatic, with a 2 °C increase by itself producing a simulated reduction in mean annual runoff in excess of 50%. The reasons for this are that under present climatic conditions evaporation losses there are relatively low from the moist soils in winter, but that with warming, faster drying soils between rainfall events significantly reduce runoff. The most significant sensitivity to climate change, however, remains that due to rainfall, with changes by one unit manifesting themselves as runoff changes by a factor of 2 to 5 (Fig. E.27, bottom), with the sensitivity more dominant in the extreme south-west.
Conclusions

This chapter has provided examples of hydrological risk from South Africa. The examples bring to the fore two overarching issues in hydrological risk management. The first is the question of uncertainty in risk-related hydrological studies – uncertainties regarding meteorological and catchment conditions now and in the future, and uncertainties around input data and uncertainties emanating from the models used in hydrological risk management. The second revolves around the recurring theme of the hydrological system’s potential for amplifying perturbations of the climate drivers, predominately of rainfall. It is the amplification and the uncertainty issues which will need to be stressed to practitioners and managers of hydrological risk and vulnerability time and again and to which researchers will need to focus more of their attention.

Acknowledgements

Results shown and discussed in this chapter derive from research funded by the Water Research Commission of South Africa and the US Country Studies for Climate Change Programme. They are thanked for their support, as are the Computing Centre for Water Research, Lucille Perks (climate change), Mark Horan (GIS) and Jason Hallowes (forecasting), all of the University of KwaZulu-Natal.