SCOPE 27 - Climate Impact Assessment

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8 Water Resources

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8.1 INTRODUCTION

Water is an indispensable element of life, and water resources are highly sensitive to climate variability and change. Traditionally, `trial and error' has been one of the most basic approaches in the evolution of human responses to climate. In fact, the first large-scale social responses to water-related climatic impacts took form as the fluvial civilizations of antiquity and were based to a large extent on the successes and failures of many small village communities during the preceding millennia (Teclaff, 1967; Mumford, 1967 and 1970). Computerized simulation models and many other impact assessment techniques are essentially also based on the trial and error principle, and assessment is still needed to supplement learning through historic experience for the following major reasons:

1. The accelerated social and economic changes of the present age tend to create situations for which little or no historic experience is at hand. Water supply problems of large metropolitan agglomerations and industrial centers, or flood problems of rapidly growing or changing communities, are situations in which climate variability or change would affect water resources in new ways.
2. Rapid advances in science and technology not only trigger economic and social changes, they also offer new strategies and tools for coping with climatic impact, for which again little historic experience can be found. High-efficiency drilling and pumping equipment, new materials for cheap and durable pipelines, chemicals treating soil surfaces for water harvesting, high-efficiency machines and materials for the construction of dams, and canals and tunnels for large-scale and long-distance water transport are examples of new technologies available for human responses to climatic impacts (Ackerman and Löf, 1959). To explore potential applications of new technologies in adaptive responses to climate should be one of the main water-related directions of the World Climate Programme.
3. Recent technology has also reduced apparent demands for water, which often turn out to be illusory. Industrial conservation and recycling of water is widely practiced, especially when pricing incentives come into play. Some cities are renovating the great volumes of wastewater they generate, to make it available for industrial or agricultural use. Every drought brings forth new ideas that reduce urban demands for water (Meier, 1977); the 1976─78 drought, for example, resulted in many household and institutional changes in the cities of central California. Future impacts of climatic change on the supply areas of these cities will be cushioned by these proven means of reducing water use.

   The often inordinate `demands' for irrigation water, especially where it is subsidized, can be reduced by better recharge and conveyance practices, drip or sprinkler application of water, better timing of irrigations, and improvements in crop management including genetic changes and better knowledge of true water needs. These can be illustrated for California (Davenport and Hagan,1981), in East Asia (VanderMeer,1968) and in the North American Great Plains, where many technological practices can reduce the impact of drought (Rosenberg, 1978). Many water-demand reductions have been proven in such semi-arid lands as Israel and Australia: water harvesting, better on-site retention, and so on (Thames and Fischer, 1981). Where climatic change might increase rainfall and raise the level of groundwater, hydraulic management can be applied, as in the Netherlands, Finland, and even in the low-energy agriculture of Meso-America (Wilken, 1969).

4. A fourth major reason why historic experience of responses to climate must be supplemented by systematic assessment of impacts lies in the processes of climate formation. Certain types of land use (such as large-scale drainage, soil-conserving practices and irrigation) significantly alter the factors of climate formation, such as the radiation and heat balance at the land surface, as well as soil moisture and atmospheric humidity. Through this they weaken the validity of historic experience for the selection of the appropriate human responses.

This chapter deals with the 'climate─water resources─water management─society' pathway of an assessment of the impact of climate on water. Section 8.2 reviews the elements for the 'climate─water resources' relation and Section 8.3 does the same for the `water resources─water management─society and economy' sequences. Section 8.4 addresses issues of assessment integrated over the whole sequence, with emphasis on various types of societal and technological settings for water-related policy analysis and adjustments.

Complicating the human modification of the natural hydrologic system is the fact that many modifications take place unintentionally, and a wide range of human activities, including all types of land use, may intervene in the natural hydrologic processes (precipitation, infiltration, storage and movement of soil moisture, surface and subsurface runoff, recharge of groundwater and evapotranspiration).

Figure 8.1 attempts to capture some of this complexity, identifying not only the central pathway of this chapter, 'climate─water resources-water management─economy─society', as marked by the thick arrow lines, but also the feedback relationship with water as an element of the climate system and with the many human-induced modifications of the natural cycle.

8.2 THE IMPACT OF CLIMATE ON WATER RESOURCES

Water resources are essentially the products of climate (Voeikov, 1884), significantly influenced, however, by land factors. Figure 8.2 provides a structured scheme of the 'climate ─water resources' link of Figure 8.1 with inclusion of the land elements. This section is focused on two key features of that linkage: the specific parameters and roles of climate in continuously, redistributing the earth's water resources, and the present state of knowledge in quantifying these relations under various sets of natural and man-made conditions.

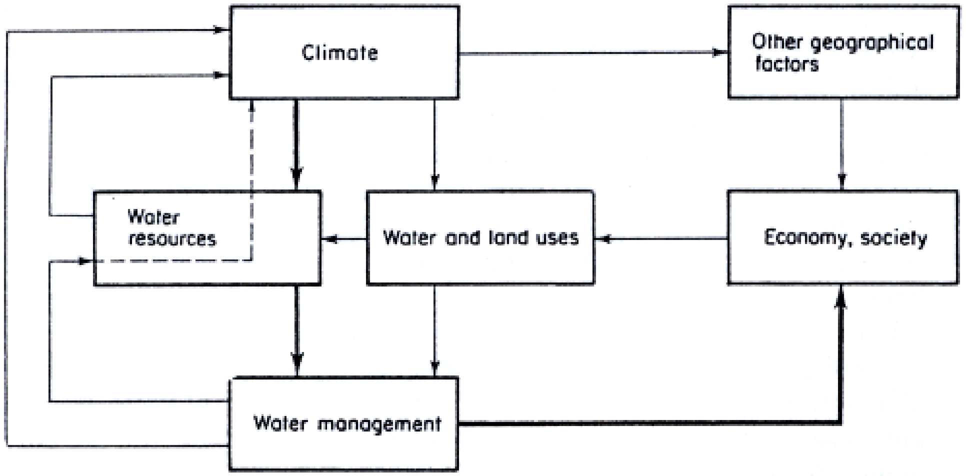


Figure 8.1 Conceptual scheme of water-related climate impact assessment

8.2.1 Climate and Water

Water in the different domains of the earth displays different rates of turnover and so reflects climatic fluctuations occurring at different time-scales. For example, a brief extension of the rainless period between summer rainstorm; can bring about a large increase in the number of days with low soil moisture, it which crops suffer moisture stress.

Longer fluctuations may reduce the level of upper groundwater and the base flow in streams, on which many urban and industrial uses depend. Such a drought may be exacerbated by societal factors, as occurred in Pennsylvania in 1980–81(Perkey *et al.*, 1983). Still longer fluctuations in climate change the level of large lakes and affect navigation, hydropower production, and riparian access, as in the Laurentian Great Lakes (Phillips and McCulloch, 1972). Very long fluctuations affect vegetation cover and even soil; allied with short-sighted practices of land management, they may result in desertification (Biswas and Biswas,1980; Kovda,1980).

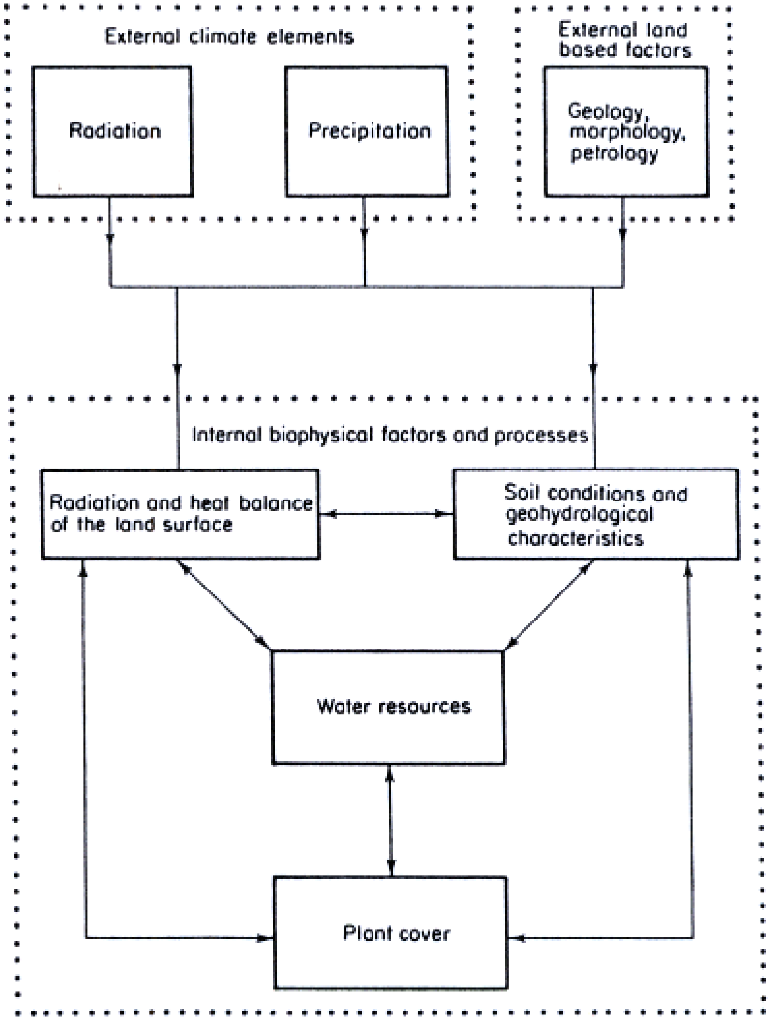


Figure 8.2 Conceptual scheme of the climate-water resources relationship

8.2.1.1 Land Factors

Land factors of morphology, soil, and plant cover, as shown in Figure 8.2, play an important role in mediating the impacts of climate fluctuations on the hydrosphere. These factors determine the storage of water on the surface or in the soil, percolation to groundwater, evaporation, and runoff. Their role is particularly significant over short periods of time in humid areas; their effects in arid and semi-arid lands are long-lasting. L'vovich (1969, 142) finds that changes in land-surface management in the Dnieper Basin are likely to decrease storm flow in rivers by 9 mm annually and increase base flow by 1 mm, for a net loss of 8 mm. In arid and semi-arid areas the impact of land factors on evaporation can exceed those of climatic variation (Sokolowsky 1968). These impacts can be expressed in one or another index of aridity (Thornthwaite, 1948; Szesztay, 1965; Budyko, 1974, 324–335; Mather, 1974, 112–120). The process of desertification, now serious in many parts of the globe, is a nearly irreversible change in vegetation, land utilization and even soil resources; the consequences of overgrazing plus drought in the 1890s are still evident in western New South Wales.

Large-scale intervention into land factors can be illustrated by drainage and flood-control works in the Tisza River basin in Hungary in the middle of the last century. Until that time, flood flows from the surrounding mountains had regularly inundated the center of the basin, to the extent of 16,000 km^2. In an average year about 2 km^3 of water evaporated from the flooded areas. In the middle of the last century the transition from flood-recession land and water use to market-oriented grain production, which evaporates less water, required large-scale drainage and flood control. Flood flows from the mountains are now carried away by the rivers, and while the climate has not changed there has been a substantial increase in flow of the Tisza.

8.2.1.2 Soil Climate

Soil temperature and moisture are factors of climate important to primary production and are quick to respond to a change in atmospheric circulation. The quantity of plant-available water that can be held in the root zone of most crops is of the order of 100 mm, which in the growing season can sustain crop growth only a short time; moisture stress begins to reduce photosynthetic production after less than a week of dry weather. Farmers understand the role of the soil-moisture reservoir and of the spacing between rainstorms, as has been shown for the grass-based animal agriculture of New Zealand (Curry, 1962). A climatic fluctuation that altered the habitual pattern of rainstorm spacing would have serious consequences to the economy and trade balance of this small country. An economic analysis of wool production in western Australia showed that an increase in rainfall of 10 percent averaged over a decade could reduce a manager's income by 10 percent (more water in the wet season brings no benefits); a decrease averaging 10 percent could cut farm income by nearly two-thirds and double the risk (Arnold and Galbraith, 1978).

Agriculture in most regions is closely attuned to the frequency of days of soil-moisture deficit (Mather, 1974, 207–213; Zur and Jones, 1981). Any climatic fluctuation that would increase the number of stress days would have an immediate impact on crop yield, whether of corn (Dale and Shaw, 1965) or pulpwood growth (Bassett, 1964), up to the point of complete loss, as in the North American middle west in the 1930s.

8.2.1.3 Groundwater

Climatic fluctuations that persist over long periods affect first the shallow groundwater resource, hence domestic wells and the base flow in small streams used for irrigation. These changes in the water table cause wells to go dry or at the least necessitate the lowering of pumps, may require the hauling of water for livestock, and impair the habitat of aquatic life.

Longer fluctuations have an impact on deep aquifers, reducing water pressure, permitting compaction and resulting land subsidence, and sometimes the intrusion of saline water. The effects observed on a local and regional scale as a result of overpumping in many places give an indication of the potential effects of prolonged drought or other reductions in aquifer recharge. For example, introduction of fall plowing and other practices in the central Chernozem area of the Soviet Union have the potential to increase recharge by reducing surface runoff (Grin, 1965; L'vovich, 1969, 142). In northwestern Russia, a possible climate change by the year 2020 might increase streamflow (Budyko, 1982, 243) and implies a rise in shallow groundwater and increased swamping of forest. Examples from East Africa show the effects on catchment yields, which are in part groundwater outflows, when rain forest is cut down to plant tea or when bamboo forests are replaced by pines (Pereira, 1973). Groundwater storage, a useful cushion over short fluctuations in climate, is vulnerable to long fluctuations.

8.2.1.4 Streamflow

River water, which has a relatively short turnover period and is a major source of fresh water, has great importance for humankind. The classification of climate from the point of view of surface flow can conveniently be based on precipitation and potential evapotranspiration, which can be tied to solar radiation or air temperature (Thornthwaite, 1948; Szesztay, 1965; Mather, 1974, 112–122). On the basis of these parameters, combined into an aridity index based on the ratios of evapotranspiration to precipitation, nine types of climate are specified (Figure 8.3). Water flows on the surface in four of the nine types (about 62 percent of the 149 million km^2 total land area), and is frozen in polar ice and glaciers over 12 percent of the land area; in 26 percent, there are deserts and semideserts without permanent surface water. Land areas with different types of surface water have varied historically as the climate of the Earth has changed.

Fluctuations of the Danube River's discharges during the period 1948–68 can be related to the fluctuations of climatic elements, specifically, to the fluctuations of ocean surface temperatures in the northern part of the Atlantic ocean (Nováky, 1981). For small catchments or low flows, the variability of surface flow is amplified, because runoff is a residual of precipitation and evaporation, and its variability surpasses the variability of precipitation, particularly in areas with little runoff (Schaake and Kaczmarek,1979). This is illustrated in Figure 8.4 for selected catchment areas in the Tisza River basin (Nováky,1981).

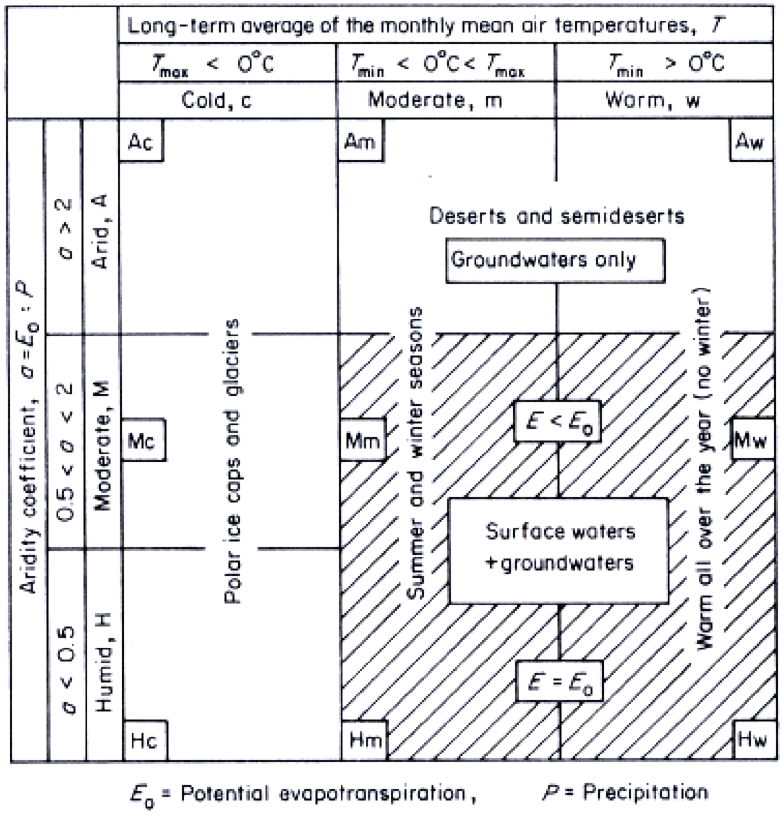


Figure 8.3 Classification of land surfaces according to climate. (Source: Szesztay, 1965)

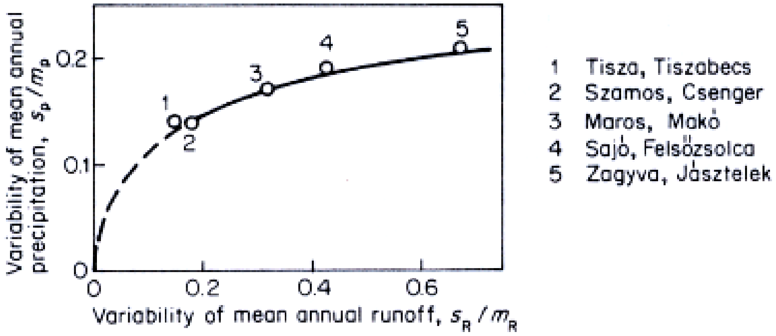


Figure 8.4 Relationship between the variability of mean annual precipitation and the variability of mean annual runoff in the Tisza River basin

8.2.1.5 Lakes

The impact of climatic changes can be analyzed particularly well in those elements that have a character of storage and accumulate climatic impacts over long periods, such as deep groundwater and lakes. The water level of the Caspian Sea has decreased since the middle of the past century. Water withdrawals for irrigation for water supply played an important role in this decrease, but it was also the result of climatic changes in the drainage area. Winter precipitation decreased, and summer temperatures increased, which led to an increase in evaporation and to a decrease in the flow of the Volga River. The change in water level of the Caspian Sea followed the change of climatic elements with a time lag of 15 years (Klige,1978).

8.2.2 Quantifying Climate─Water Resource Relationships

In quantifying the climate─water resources relationship, transfer functions are used to transform climatic characteristics into water resources. Transfer functions are classified by Schaake and Kaczmarek (1979) into three categories: statistical, analytical and numerical. The theoretical base becomes more complete in progressing from the statistical through the analytical to the numerical models.

Statistical transfer functions are, for example, the empirical relationships between proxy information on fluctuations of climate (such as tree-ring indices or glacial activity) and water resources. Analytical transfer functions are based on simplified physical principles, such as the balance between climate elements (for example, precipitation, evaporation) and water resources (runoff, change of storage in soil moisture, etc.). Numerical transfer functions are based on conceptual hydrological models, which allow for more detailed physical considerations than the analytical functions but also require digital computers for their application.

As Schaake and Kaczmarek (1979) comment, the application of any transfer function is limited by three main technical factors:

1. the inherent accuracy of the model,
2. the degree to which model parameters depend upon the climatic conditions for which the model was calibrated,
3. the accuracy of the input data.

The climate─water resources relationship must be based on characteristics of climate aggregated over the long term, especially precipitation, its mean annual and seasonal values, monthly values and dispersions. The third point above must be kept in mind: many climatic measurements are of dubious accuracy, especially in recent decades, and rainfall data are notoriously defective (United Nations, 1972, Chapter 2; Mather, 1974, 51─56, 100; World Meteorological Organization, 1975,13, 23).

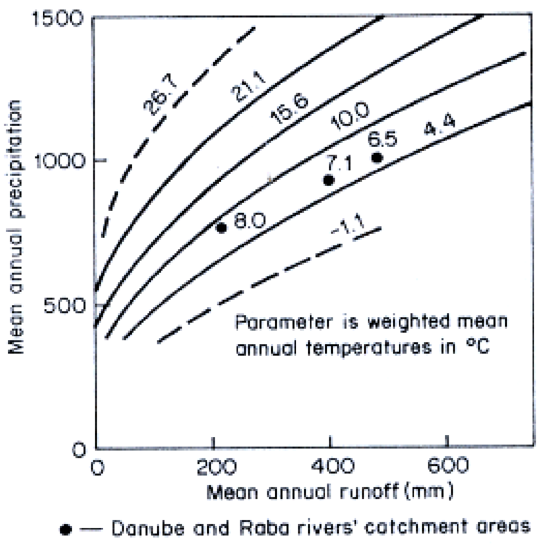


Figure 8.5 Relationship of annual runoff to precipitation and temperature. (After Langbein,1949)

The relationship of mean annual streamflow to precipitation and temperature was evaluated by Langbein (1949) for regions of the United States (Figure 8.5), and a tentative analysis of data from the Political and Economic Atlas of the World (edited by the Hungarian Cartographical Institute, 1974) suggests that this relationship can be applied to other regions of the world. Mean annual streamflow, precipitation, and air temperature in the drainage area of the Danube River and its tributary, the Raba River, are well in line with the relationship elaborated by Langbein.

Another model relates to Lake Balaton, the largest lake in Hungary, with a surface area of about 600 km^2. The precipitation on the surface is 630 mm, the inflow from the drainage area is 880 mm, and the total supply is 1510 mm. This total supplies 870 mm evaporation and 640 mm regulated outflow. The balance of these elements is presented in Figure 8.6 (after Szesztay,1960). Suppose a change of climate around the lake such that it would be similar to the present-day climate in the middle of the Tisza River basin; for example, suppose an increase in temperature by 0.5 °C and a decrease in annual precipitation by 5 percent. These relatively slight changes in climate would result in a significant change in the life of the lake: evaporation from the lake surface would consume most of the precipitation and inflow, and outflow would decrease to a tenth of its present value. Lake Balaton would become nearly a closed inland lake, with a water surface smaller than that of today. The renewal of the lake's water would be slower, which would have an effect on water quality and biological regime.

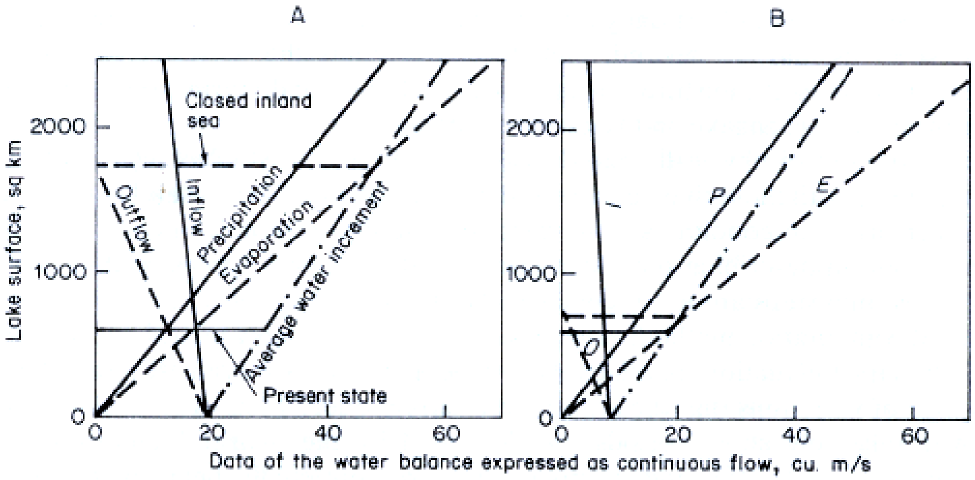


Figure 8.6 Water balance of Lake Balaton, plotted against the lake surface. A, under present climatic conditions (after Szesztay, 1960) and B, under simulated climatic conditions

Two complicating factors should be noted: the role of water itself in the formation of climate, and the human modifications in water fluxes, especially those at the land surface.

Water is an internal and almost ubiquitous factor in the processes that form weather and climate, because it stores, transports, delivers and redistributes energy in many ways and at many scales. Water is not an external parameter of climate formation but rather plays an important role in the biophysical impacts of climatic changes, as well as in the responses of climate to biophysical changes. It is therefore a key element in the assessment of every human-caused climatic change, and water management is a prospective tool for influencing climate formation. In fact, the impact of water management on certain elements of the local climate is frequently quite rapid and obvious (as in the case of large-scale drainage or irrigation), whereas impacts along the 'climate–water management' line usually remain slow and indirect. The impact of water on climate belongs, however, to the climate research sector of the World Climate Programme and lies essentially outside the scope of the present paper.* Nonetheless, these and land-related feedbacks complicate the quantification of climate-water resources relationships.

Both the feedback relationships of water in climate processes and the effects of human activity on water fluxes can be incorporated in models of the climate-water relation. These models accept inputs of climate or weather data, expressed in monthly or daily measurements (Willmott,1977) or in time-steps as short as may be desired, and develop outputs that describe the water resources of soil moisture, groundwater recharge, and storm flow and base flow in rivers (Schaake and Kaczmarek,1979).

* In order to acknowledge this linkage, major aspects of the `water management-climate' pathway have been reviewed in one of the preparatory papers of this study program (Szesztay, 1981).

A number of physically based hydrologic models exist (Peck *et al.,* 1981), beginning with those that develop flash floods on small rivers, useful to validate information on conditions of terrain, soil and drainage networks of a basin. Precision in describing these conditions lends confidence to estimating their role as time-steps are lengthened to 6 hours to a day or more. Availability of rapid computation methods now makes it possible to apply hydrologic models to climatic fluctuations of relatively great length, and so to evaluate more of the range of variations that the atmosphere can produce. Tests of several models over relatively short periods are described by the World Meteorological Organization (1975), and improvements are continually being made. The SSARR model (US Corps of Engineers, 1975), for example, was verified in the upper basin of the Missouri River (Cundy and Brooks, 1981).

Nemec and Schaake ran the Sacramento soil-moisture accounting model (Burnash *et al.,* 1973) at 6-hour time-steps over periods of 12 years for a river basin in Texas, defining 16 parameters that describe the upper and lower soil zones and percolation from them. The calibrated model was then run under different postulated values of rainfall and air temperature (as a means of incorporating the energy input that drives evapotranspiration), and produced the probable streamflow, the reservoir storage required to obtain a specific degree of river regulation that will produce yield equal to 0.2 of mean annual streamflow, and reservoir yield. A model for a humid river basin was similarly calibrated and run, giving comparative responses of that basin to an increase or decrease in rainfall. In both basins, a change of 0.01 in rainfall produces approximately 0.02 change in reliable yield from reservoirs (Nemec and Schaake,1982).

Stochastic models are sometimes used to evaluate the probable range of variation in future streamflow, using analyses of the statistical properties of the past record. These records, however, are even more limited than those of rainfall, and evaluation of extremes is risky, whether these be design floods or prolonged low flows. Stochastic models of rainfall, usually the most important input into such hydrologic models as the Sacramento or SSARR, also help define some of the range of fluctuations in atmospheric deliveries of water, although the fact that every year rainfall records are broken by the dozen by new extremes reminds us that nature has a great potential to surprise us. The concepts of probable maximum precipitation, having a base in physical hydrometeorology, and probable minimum flow, using geological factors, are useful in designing water resource developments. However, in using all these hypothetical constructions it must be kept in mind that longer-range variations in climate are hardly being adequately sampled by the available records.

Rainfall itself is a crude output of some of the larger models of the atmospheric circulation, such as those run to foreshadow possible effects of increased atmospheric carbon dioxide. Only the largest models attempt to produce longitudinal differences in the zonally averaged outputs, so regional information is often approximate. The value of general circulation models for regional hydrologies is therefore not clear at the present time; yet the critical impacts of climate upon water resources are those that occur at regional scales, like the Colorado River basin in the southwestern United States. Partly as a consequence of relying on unrepresentative streamflow data, this relatively small river has been over-allocated, and societal institutions are overtaxed to manage present-day flow resources (National Research Council, 1968; Dracup,1977; Peterson and Crawford,1978). The low quality of the river water exacerbates the management problem, and has given rise to further hydrological modelling efforts (Clyde *et al.,*1976).

The effects of changes in land management in a river basin can be evaluated by changing basic parameters in hydrologic models, which focus on processes at the surface of the earth and the immediately underlying soil layers. Properties of the surface, soil, and vegetation, which with over-use may be degraded hydrologically, can be entered in the models to evaluate the consequences of abuse of the land. Good practices that maximize the infiltration of rainwater into the soil and minimize storm flow can be expected to reduce the impact of a climatic fluctuation on the societal value of the water and biological productivity of a region. Moreover, it should prove possible to evaluate the economic benefit of good management practices that improve the status of soil moisture and photosynthetic production, the stability of groundwater and streamflow, and regulated storage as resources of a region.

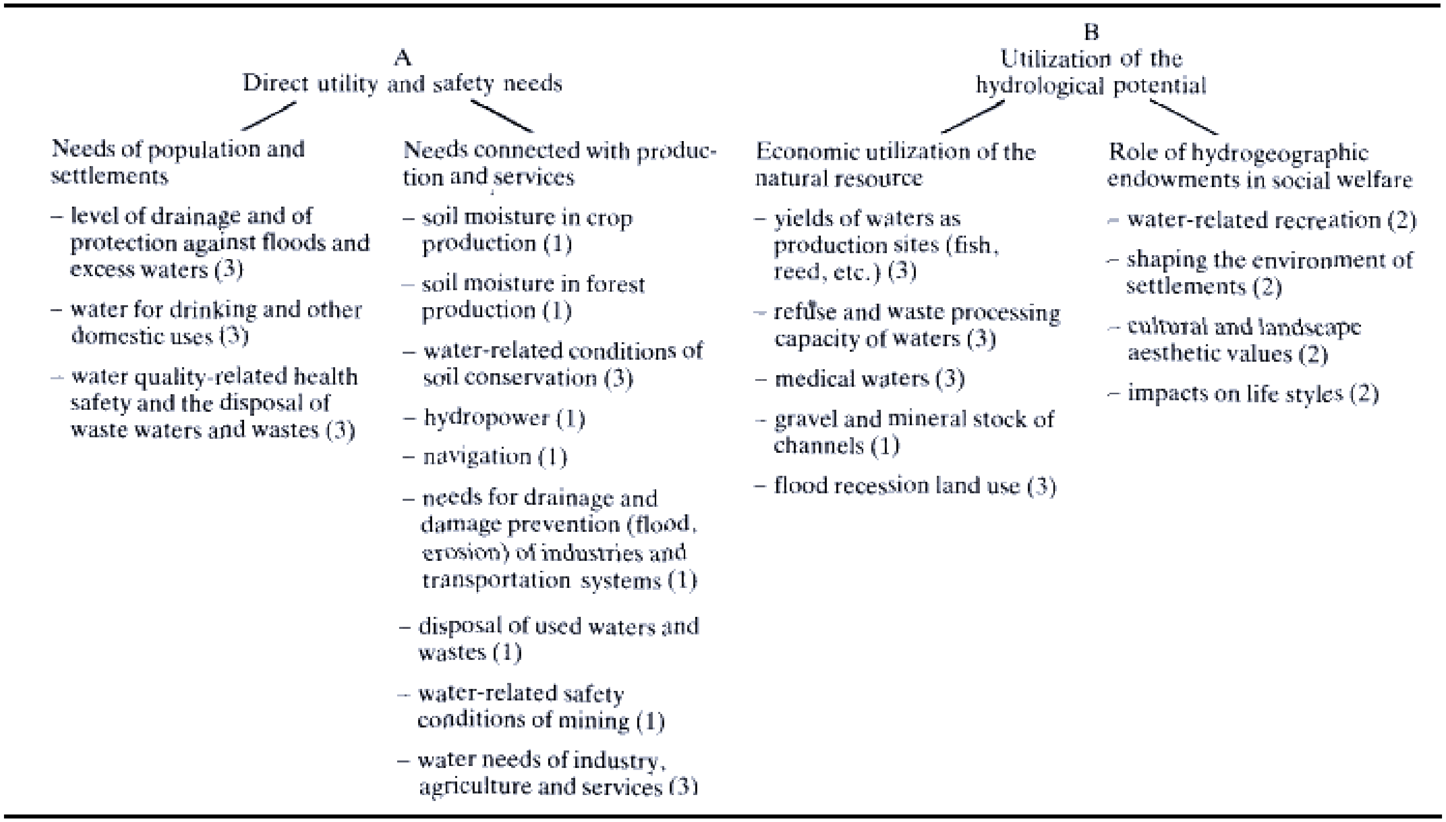
8.3 THE SOCIETAL CONTEXT OF WATER-RELATED IMPACTS OF CLIMATE CHANGE

Given a transfer function between climate variation and water resources, it is then necessary to transform the physical quantity and availability of water into economic and social values. This can be done by identifying the socially significant attributes and factors of the hydrogeographical endowments and hydrological processes of a given area and the major means of water management in satisfying society's demands for water-related services, taking into account human as well as climate impacts.

8.3.1 Use and Purpose in Water Resource Development

A climate-induced increase or decrease of water resources takes on value only in terms of the actual or potential benefits and hazards to humans. A classification of these attributes in terms of water-resource use and purpose is given in Table 8.1, in which `utility and safety' that are directly related to human habitat and production are separated from `hydrological potentials', which are less directly associated.

Table 8.1 Water resources use, purpose, and evaluation methods



A Direct utility and safety needs		B Utilization of the hydrological potential	
Needs of population and settlements	Needs connected with production and services	Economic utilization of the natural resource	Role of hydrogeographic endowments in social welfare
– level of drainage and of protection against floods and excess waters (3) – water for drinking and other domestic uses (3) – water quality-related health safety and the disposal of waste waters and wastes (3)	– soil moisture in crop production (1) – soil moisture in forest production (1) – water-related conditions of soil conservation (3) – hydropower (1) – navigation (1) – needs for drainage and damage prevention (flood, erosion) of industries and transportation systems (1) – disposal of used waters and wastes (1) – water-related safety conditions of mining (1) – water needs of industry, agriculture and services (3)	– yields of waters as production sites (fish, reed, etc.) (3) – refuse and waste processing capacity of waters (3) – medical waters (3) – gravel and mineral stock of channels (1) – flood recession land use (3)	– water-related recreation (2) – shaping the environment of settlements (2) – cultural and landscape aesthetic values (2) – impacts on life styles (2)

Evaluation possibilities:	(1) Analytical methods (2) Based on social policy criteria (3) Joint consideratio +n of economic and social criteria

After Orlóci and Szesztay, 1981.

The industrialization of recent centuries was usually accompanied by a shift from hydrologic potentials toward growing interest in the groups of direct utility and safety. In Hungary, for example, during the period from the eleventh to the eighteenth centuries, economic stability was largely based on a traditional system of flood-recession land use along the Danube and Tisza Rivers and their major tributaries. In the sophisticated and productive system of land use, annual flooding was not prevented but was rather promoted and regulated in order to achieve high yields and a variety of foodstuffs (fish, cattle, poultry, fruits, grain, vegetables, honey) and to provide power and transportation by watermills and inland waterways (Andrásfalvy, 1981). The gradual replacement of this traditional economy by market-oriented grain production and industrialization during the eighteenth and nineteenth centuries required large-scale drainage and flood-control works affecting more than a third of the present area of the country.

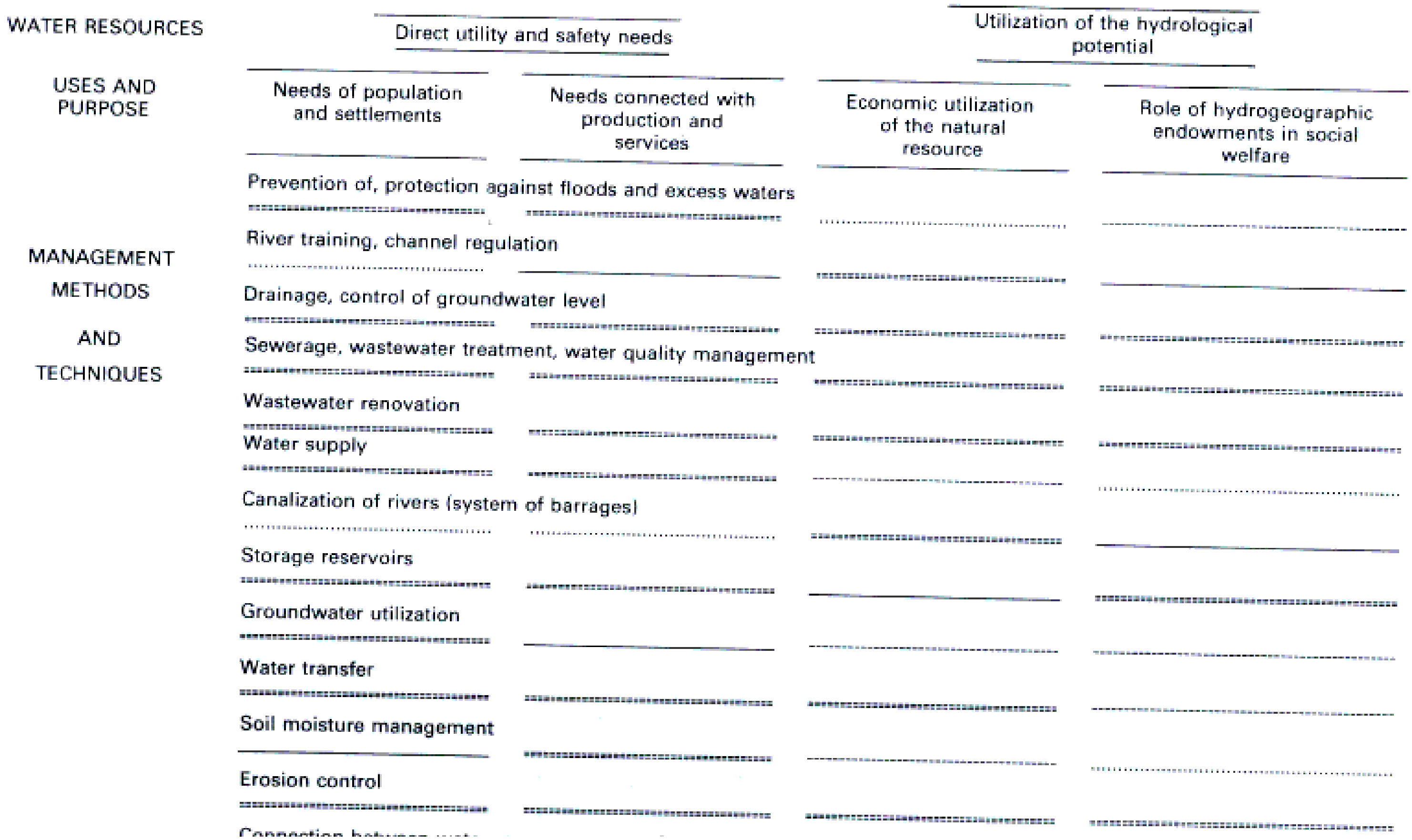
For each of the socially significant attributes of water resources listed in Table 8.1 there exist approaches and methods by which the nature and extent of social interest can be described and quantified. These include the conventional methodology of economic analysis (see the items marked by `1'), evaluations based on verbal descriptions and social policy criteria (items marked by `2'), or on a joint consideration of the previous two approaches (items marked by `3'). The suggestions of Table 8.1 are tentative and much will depend on the availability of data and on other local conditions in any given case. Commonly, the analytically assessable attributes of water belong to the group of direct utility and safety needs connected with production activities, and the socially significant attributes are assessed by verbal descriptions and social policy criteria.

8.3.2 Water Management Techniques

For each preference with regard to the socially significant attributes of water there exist specific methods and technologies through which the demands for water and water-related services are satisfied. In a narrower sense the technologies applied in satisfying water-related demands are summarized under the term `water management' and they include the 12 groups of activities listed in Figure 8.7, with the indication of their linkages to the four groups of social demands and interests of Table 8.1.

8.3.3 Climate–Water Management Sensitivity

Major water management activities are variously affected by climate events, depending on their time-scale: within-year weather, yearly fluctuations, multiyear variations, and century or longer changes. Each management activity can be evaluated as to its sensitivity (Table 8.2) and its reliability (National Research Council, 1977), as well as its ability to recover after a failure and the likely consequence of a failure (Cohon, 1982).



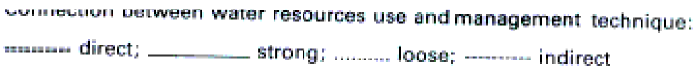


Figure 8.7 Water resources, purpose and management methods

Table 8.2 Sensitivity of water management to climatic events

Management methods and techniques	Sensitivity to climatic events			
	Within-year	Annual	Multiyear	Century
Protection against floods	X	X		
River training	X	X	X	
Drainage		X	X	X
Water quality management	X	X	X	X
Wastewater renovation		X	X	
Water supply		X	X	X
River canalization (dams)		X	X	
Storage reservoirs		X	X	X
Groundwater utilization		X	X	X
Water transfer		X	X	X
Soil-moisture management	X			
Erosion control	X			

8.3.4 Human Activity-Water Resource Sensitivity

The socially significant attributes of the water resources of a given region are determined and influenced not only by climate and other environmental factors; they may also be altered and affected to a considerable extent by human impact upon the environment. Water-related climatic impacts can be assessed and evaluated only if they are large in comparison to hydrologic changes caused by humans, and if the climatic and the human impacts can be reasonably separated. For this reason the assessment of human-caused hydrologic changes should go hand in hand with the assessment of water-related climatic impacts. Figure 8.8 offers a structural scheme and a few indicative examples for such an assessment.

It is obvious that water management activities, that is, water use and regulation, always have impact on hydrologic processes, but perhaps less obvious that land uses also alter the hydrologic regime, and that these alterations frequently exceed those caused by water management activities (as, for example, in the case of large-scale mining operations, chemicalized agricultural land use, or toxic metals in industrial wastewater entering a lake). In order to arrive at a definite conclusion with regard to the social significance of human-caused hydrologic changes, the sequence of impact assessment indicated at the bottom of Figure 8.8 is important. Changes in the societally significant attributes of the region's water resources constitute the concluding phase of the assessment procedure.

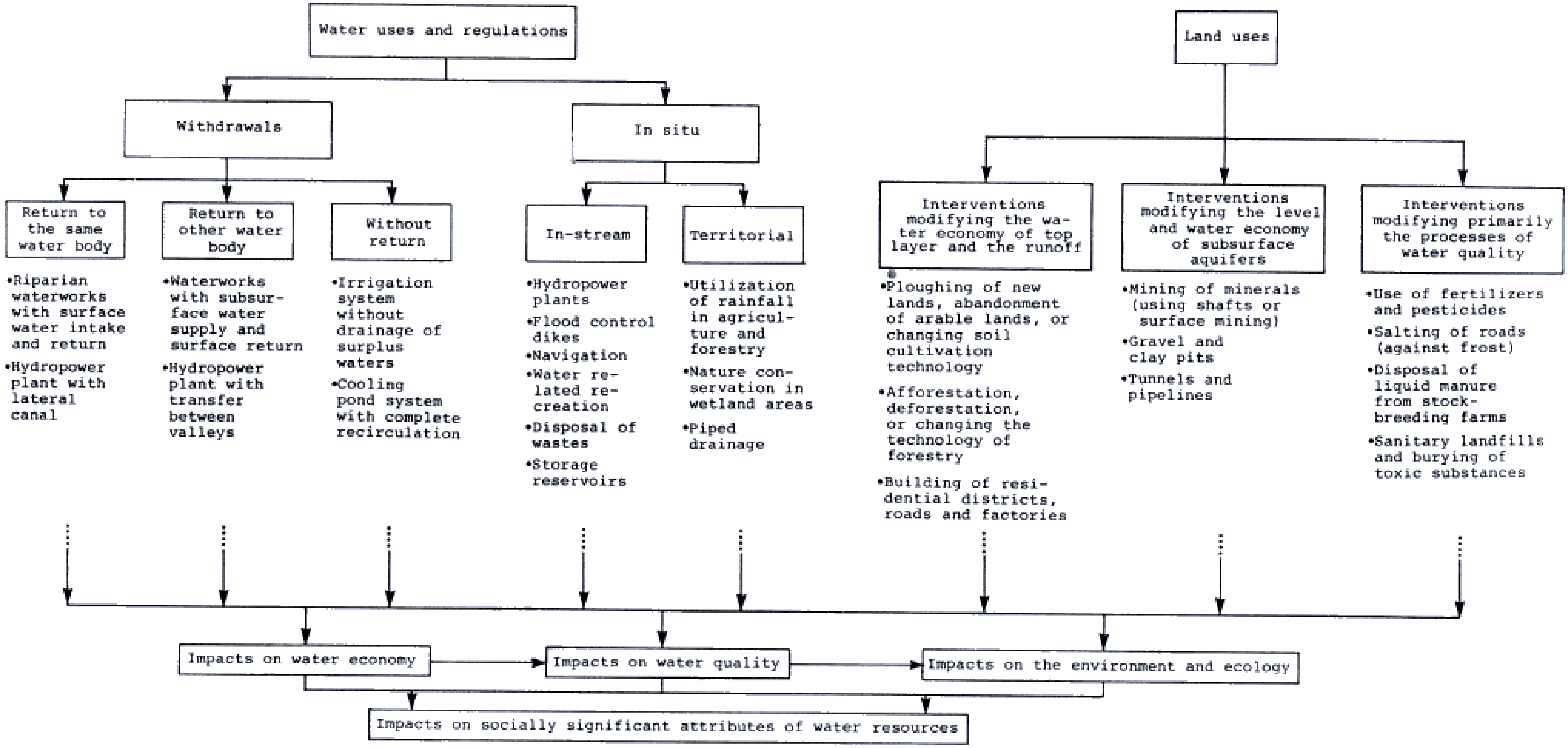


Figure 8.8 Impact of human activities on hydrology processes and their feedbacks on society (structural scheme with indicative example. (After Orlóci and Szesztay, 1981)

8.4 INTEGRATED ASSESSMENT OF WATER-RELATED CLIMATIC IMPACTS

8.4.1 Defining Assessment Objectives

While climate as a key element in hydrology for water management is often studied, integrated climate impact assessment is rare. A beginning point for such assessment is to select and define a few specific assessment objectives.

To look at a country's (region's) water management in its entirety and its historical evolution as a specific human response to climate could be a sound point of departure. A general survey could identify characteristic levels and turning points in water management, and compare them with corresponding levels and trends in the region's climatic and social conditions. Policy-oriented global reviews on major issues of water management (Falkenmark and Lindh, 1976; United Nations, 1976; Szesztay, 1982) could help in the formulation of questions that should be asked, and analytical studies on related topics (Kates, 1981) could provide guidance on methodological approaches that could be applied in such regionwide surveys.

Settings in which relatively small changes in climate might trigger substantial consequences in water resources and water management deserve particular attention. Shallow lakes can dry out or reappear under the cumulative effects of relatively small changes in aridity. In a cold climate, the snow line as well as river and lake ice are affected by relatively small consecutive fluctuations in winter temperatures. Revelle and Waggoner (1983) have shown that warmer air temperatures and a slight decrease in precipitation would probably severely reduce both the quantity and quality of water resources in the western United States, and that similar effects can be expected in many water-short regions elsewhere in the world.

In formulating assessment projects, priority generally should be given to regions and situations where relatively small changes in the water-resources regime might produce significant consequences in water management and its societal implications (regions where withdrawals are close to the dependable river flow resources, densely populated or intensively cultivated flood plains).

8.4.2 Assessing Climatic Impacts by Matrices

After having defined the scope and objectives of the assessment program in the light of current issues of water management planning and policies, the implementation of the program should proceed. Three interrelated phases of implementation can be distinguished:

1. identification of the particular attributes of the water management system that are sensitive to climatic impacts (Section 8.3);
2. identification of specific elements of climate that affect the system indices (Section 8.2.1);
3. formulation of the relation between climatic parameters and water management factors in terms of impact functions (Section 8.2.2).

These steps can be brought together in two illustrations: the metropolitan water supply system of the northeastern United States and an analysis of floods.

Based on a thoughtful effort to investigate how sensitive are the large metropolitan water supply systems of the northeastern United States to climatic change, Schwarz (1977) prepared Table 8.3. Of nine attributes of the systems which are judged to respond significantly to a change of climate, Nos. 1─4 relate to the 'climate─water resources' part of the impact scheme and express changes in the quantity and quality of water available for supply, and Nos. 5─9 relate to the `water resources─water management─society' part and describe technical, economic and managerial aspects of system operation. Five climate fluctuations are confronted in the table with these nine system attributes.

Table 8.4 contains a similar matrix of the impacts of climatic change on flood hazards under various hydrologic conditions and managerial situations. Four flood-hazard situations are shown in this table against four variations of climate. The matrix emphasizes the fact that the relevant parameters of climate differ, even in the same group of water management activities, with the size and composition of the system.

Flood-hazard simulation is the one major field of water management in which a sound basis and relatively rich experience are available, mainly as a result of the work of a group under White at the University of Chicago and his later Natural Hazards group at the University of Colorado.

8.5 CONCLUSION

In this chapter, the authors have tried to describe some of the manifold ways in which fluctuations in atmospheric circulation and climate might alter the water resources of a river basin, region or nation. These fluctuations occur at many time-scales and have correspondingly diverse impacts on water resources: impacts on the resources of soil moisture and storm flow occur at short time-scales; those on groundwater, base flow in rivers, and the level of large lakes occur at long time-scales, represent a different kind of alteration in the circulation of the atmosphere, and are immune to short-period fluctuations.

Table 8.3 Speculative water supply impact matrix of climatic change

	Parameters of climatic change				
Attributes	A	B	C	D	E
of water supply systems	Decrease in mean streamflow	increase in variance of streamflow	Increase in skew of streamflow	Increase in persistence of streamflow	Speed with which change occurs
1. Yield from unregulated streams	Some effects, but likely not very large except if change in mean is large or combined with other changes	Severe effects; however, generally short term	Significant effects because number of days of low flow increase relative to few high flow periods	Significant effects more through duration of low flows than severity	Not applicable
2. Yield from reservoirs	Significant to severe effects particularly if reservoirs develop a high percentage of the average flow	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Significant to severe effects especially if reservoir long-term storage is limited	Not applicable
3. Yield from groundwater	Significant in the long run, especially if draft on aquifer is near average recharge	Little if any significance	Little if any significance	Effects severe and of long duration	Not applicable
4. Quality of raw	Probably	Generally no effects	Little if any	Little if any	Not applicable

water	insignificant effects except where large reservoirs are drawn to very low levels	except possible increase in turbidity during high flows	significance	significance	
5. System reliability	Some effects, other than effects accounted for under 1–4	Some reduction due to constant change in flows in addition to effects under 1–4	Little or none, other than effects under 1–4	Little or none, other than effects under 1–4	Sudden changes severely affect reliability, slow ones less or not at all
6. Effectiveness of intersystem and interbasin connections	No change	Increased effectiveness if variance increases	Little effect	Reduced efficiency of interconnections because long droughts are usually also widespread	No change
7. Magnitude and control of demand	No significant effect	No significant effect; often reccurring short-term restrictions may reduce their effectiveness	No significant effect	No significant effect; emergency restrictions likely to become less effective over long droughts	Significant and visible effects, relatively fast changes could force major steps toward conservation and demand control
8. Cost of operation of water system	No significant effects except for additional construction that might eventually ensue to alleviate long-term shortages	Possible increase due to turbidity, increased pumping between systems if applicable; possible additional reservoir construction	No significant effects likely	No significant effects except search for new sources	No effects
9. Pressure on and ability of the water system to respond to change	Pressure for expansion would be created if shortages occur repeatedly; ability to respond would	Pressure for expansion would be created, but rapid return to normal may for some time inhibit	Pressure for expansion would be created if shortages occur repeatedly; ability to	Pressure for expansion would mount over time and increase likelihood of action; however, long	Sudden or relatively near future changes could increase action; long-term changes (20 years+) even

not be affected by hydrologic event	expansion	respond would not be affected by hydrologic event	high flow periods may inhibit development	if known would likely be ignored by existing institutions

Reproduced with permission from Schwarz, 1977,116–117.

Table 8.4 Speculative flood hazard impact matrix of climatic change

Attributes of flood hazard management systems		Parameters of climatic change			
		Increase in short-term peak intensity or rainstorms	Increase in average intensity or duration of rainstorms	Increase in average intensity or duration of the snow melting period	Increase in persistence of multiannual cycles without exceptional or catastrophic floods
Small urban or rural catchment areas	with flood retention reservoirs	Slight impact on reservoir operation	Significant revision of reservoir design and operation, or increase of flood hazard	No or little impact	Slight to high increase of flood hazard due to unwarranted intensification of land use in the risk area, and to insufficient maintenance of flood control installation and services
	without flood retention reservoirs	Slight to medium increase of flood hazard	Medium to significant increase of flood hazard		
Large river basins	with flood recessive land and water use	No impact	No or little impact	Change in land use pattern with no or very little damage	
	with dike system along the major streams			Significant revision of dike system design and operation, or very substantial flood losses	

The impact on soil moisture, groundwater, and storm and base flow resources of a change in water or energy delivered to a river basin can be evaluated by several kinds of models.

Particularly useful is the conceptual hydrologic model that reconstitutes basin hydrology under changing weather at short time-steps and collects the data into periods of years or decades, as appropriate. These changes in the resources of soil moisture adequacy, streamflow, and groundwater can then be assessed in terms of possible ameliorative or coping technology and management practices.

In order to select these technologies and practices in a socially desirable way, all those properties of the hydrogeographical endowments and hydrologic processes that are of actual or potential benefits or hazards to man within the given region should be assessed. For the purposes of analytical evaluation these socially significant properties should then be tied to water-related climatic parameters via impact matrices or other tools of correlative description.

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