Pergamon

Phys. Chem. Earth (B), Vol. 25, No. 3, pp. 221–226, 2000

1464-1909/00/$ - see front matter

PII: S1464-1909(00)00007-1

Water Supply in the Long Term: a Risk Assessment

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Received 26 April 1999; accepted 9 August 1999

Abstract. Integrated water assessment studies are often confined to a study of physical aspects, considering the relation between surface and groundwater, water quantity and water quality, and between water, land and climate. The interaction between changes in the water system and socio-economic development is then left out of the analysis. The AQUA tool has been designed to analyse the dynamic interaction between long-term socio-economic development and changes in the water system. The implementation of different perspectives in the model allows for a perspective-based scenario development and assessment of policy risks. The analytical results show that the integrated approach can improve the understanding of how water can be both an opportunity for and a barrier to development.

1 Introduction

Since people have started to speak about sustainable water resources management, it has become clear that an integrated approach towards water problems is a precondition. But what does integration mean? The usual approach is to explain the idea of integration through its historical evolution. One can distinguish three successive stages or levels of integration (Mitchell, 1990). On the first level, integration means the systematic consideration of the various dimensions of water: surface and ground water, quantity and quality. The key aspect here is the recognition that water comprises a system formed by a number of interdependent components. On a second and broader level of integration, water is seen as a system that interacts with other environmental systems, such as land, soil and climate. One takes the step from *internal* integration within the water field towards *external* integration with surrounding fields. On a third and even broader level of integration, water is considered in relation to social and economic development. Here, the concern is to determine the extent to which water is both an opportunity for and a barrier to economic development, and to ascertain how it is possible to ensure that water is managed and used so that development can be sustained in the long term. Currently, most of the 'integrated' water assessment studies are confined to the first or second level of integration. However, the third level of integration would deserve most attention, because many of today's water problems can probably only be solved through a comprehensive outlook and set of measures.

Integrated research focuses on the interaction between diverse processes, rather than on the nature of a few particular processes. A major problem in this type of research is that it provides knowledge that gives some *understanding* of the interaction between diverse processes, but that it does not enable us to make meaningful *predictions*. The type of uncertainties involved requires an explorative approach, which regards uncertainty as inherent in knowledge and which explicitly shows that there is room for diverse assumptions and hypotheses. Such an approach is of crucial importance in the development of scenarios and the formulation of an effective development policy, because basic assumptions strongly influence the outcomes of these processes.

This paper describes the results of a research study that aimed at the development of a generic tool for integrated water assessment, where 'integrated' was understood at the third, most comprehensive level and where the proper treatment of uncertainties was one of the major concerns (Hoekstra, 1998; Rotmans and De Vries, 1997). The second section discusses the methodology followed. The third section gives a brief account of AQUA, the tool that has been developed in this study. The fourth section gives some of the main results and the final section the conclusions.

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2 Methodology

A methodology for integrated water assessment has been developed, which aims to:

- facilitate the analysis of the interaction between societal developments and changes in the water system,
- express the implications of uncertainties in basic assumptions in an explicit way,
- show the risks of different management strategies.

The AQUA model has been developed as a tool to support integrated water assessment. The model consists of three main components: a simulation model, a set of indicators linked to this model and a framework of perspectives to analyse uncertainties. The AQUA tool has been applied on both global and river-basin level. In the latter case, the Zambezi basin in Southern Africa has been taken as a case study.

A perspective is defined as a coherent perception (set of assumptions and hypotheses) with regard to the functioning of the world and the way people act. Four perspectives have been used: the hierarchist, egalitarian, individualist and fatalist (Thompson *et al.*, 1990). Current controversies in the water research field have been interpreted in terms of the four perspectives. According the hierarchist for instance, water demand is a given need, following from factors such as population size and economic development. Within this perception, water scarcity can only be solved by increasing the supply. The hierarchist is often described as the engineer, the bureaucrat or the technocrat. From the egalitarian point of view, the driving force behind water scarcity is the growing demand, so solutions should be found in demand management. According to the individualist, the only right indicator of water scarcity is or should be the price of water. The solution to water scarcity would then be to introduce proper pricing mechanisms. According to the fatalist, uncertainties are so large that it is difficult to say whether one type of policy would be more beneficial than another one, so the basic attitude is one of laissez-faire. For an elaborate description of the perspectives and the argumentation behind, the reader is referred to Hoekstra (1998).

The qualitative descriptions of the four perspectives on water have been translated into the model by implementing alternative equations and input data at the places in the model where the major uncertainties are located. In fact, one can speak of 'four models in one'. Both in the global and in the Zambezi study, the model has been calibrated separately for each of the perspectives, on the basis of historical data.

Before running the model one can choose a particular type of context, a world-view and a management style. The *context* refers to exogenous developments that are input into the model, such as demographic developments, economic growth, etc. The *world-view* pertains to the functioning of the part of the physical world that is represented by the model. The *management style* relates to the response behaviour of people. The management style can be chosen according to one of the four perspectives. The context and world-view can be chosen according to the hierarchist, egalitarian or the individualist perspective (the fatalist regards the world as unpredictable: the future might randomly behave like one of the other perspectives). Scenarios are constructed by choosing a certain combination of context, world-view and management style. In this way, one arrives at $3 \times 3 \times 4 = 36$ possible futures. Three of these futures are called utopias, 'ideal' futures in which context, world-view and management style correspond to the same perspective. Dystopias are scenarios in which this is not the case. Risks of different policy strategies are estimated by analysing the dystopian futures: what happens if a particular management style, which fits within a specific perspective, is applied to a world that behaves according to a different perspective. In this way, the risk concept is not defined from one perspective, but is understood at a level that exceeds the individual perspectives. Such a risk assessment can support the formulation of policy priorities that go beyond the preferences of separate perspectives.

3 The simulation model of AQUA

3.1 Schematisation of the system

The interaction between human being and the water system has been schematised by distinguishing four sub-systems: pressure, state, impact and response. The pressure system refers to a variety of human activities that affect the state of the water system. The state system refers to water stocks, flows and water quality. The impact system refers to the performance of human activities that depend on water and the functioning of ecosystems. The response system refers to human action that is undertaken in reaction to certain impacts. If put in relation to each other, the four sub-systems form a closed loop, because response feeds back to pressure, state and impact. Corresponding to this schematisation, the AQUA model consists of four interacting sub-models.

In the AQUA World Model, the simulation period is 1900-2100. In the AQUA Zambezi Model, the simulation period is 1990-2050. The time step is one year in the pressure, impact and response sub-models and in that part of the state sub-model that describes oceanic and ice-sheet processes. The time step is one month in the part of the state sub-model that describes terrestrial hydrology.

3.2 The pressure sub-model

The pressure sub-model calculates water demand from determinants such as population size, gross national product, value added in the industrial sector and demand for irrigated cropland. The model distinguishes four water-demanding sectors: the domestic, irrigation, livestock, and industrial sector. Domestic water demand is split up into urban and rural demand, and in both cases into public and private demand. Within the livestock sector, different animal types have been distinguished. The model distinguishes between four types of water sources: surface water, renewable groundwater, fossil groundwater and seawater. In addition to water withdrawals, the pressure model calculates consumptive water use (the part of the withdrawal that gets lost through evaporation), wastewater production and wastewater treatment.

For the livestock sector, specific demand is supposed to remain constant. For each of the other sectors, specific water demand is calculated as a function of economic growth (using gross national product per capita as an indicator), changes in water price and water-use efficiency improvements. The growth elasticity of demand has been assumed to be sector-specific and is defined as a function of the gross national product per capita (it is assumed that the response of demand to economic growth will decrease if a certain stage of development has been reached). The price elasticity of demand is regarded as a constant parameter, but sector-specific. Efficiency improvements are driven by technological innovation and increased public awareness. A simple logistic curve with a diffusion rate d has been assumed, to simulate the diffusion of water-conserving technology. The actual water-use efficiency Eff_{act} increases as follows:

$$\frac{dEff_{act}(t)}{dt} = d \times Eff_{act}(t) \times \left(Eff_{\max}(t) - Eff_{act}(t)\right) \qquad (1)$$

The maximum possible efficiency value Eff_{max} determines the ceiling of the logistic curve. In the case of irrigation, efficiency is defined as the fraction of the total water withdrawal that actually benefits the crop (i.e. the part taken up and transpired by the plant). The remainder consists of water losses through evaporation and groundwater recharge. The maximum possible efficiency in the case of irrigation has a natural upper limit of 100 per cent. In the case of domestic and industrial water use, efficiency is a relative concept, which means that an efficiency value has meaning only if compared to a previous efficiency value. The maximum possible efficiency is supposed to increase at a constant rate.

3.3 The state sub-model

The state model describes hydrological processes and freshwater quality. The hydrological cycle is modelled by distinguishing ten types of water store (atmospheric water, glaciers, biological water, soil moisture, renewable fresh groundwater, fossil groundwater, salt groundwater, fresh surface water, oceans and polar ice sheets) and by simulating the flows between these stores. This yields estimates of for example evapotranspiration, net precipitation, direct runoff and percolation, delayed runoff and total river runoff. These calculations are the basis for calculations of changes in water stores. Changes in the groundwater store are translated into estimates of groundwater-level decline and changes in the oceanic water store are translated into estimates of sea-level rise. For calculating evaporation and runoff, different land-cover types are distinguished. Water quality is described in terms of four water quality variables (nitrate, ammonium, dissolved organic nitrogen and phosphate) and four quality classes (good, adequate, inadequate, and poor). Good means suitable for the maintenance of natural aquatic ecosystems. Water of adequate quality does not meet natural conditions but is suitable for most human purposes. Inadequate means unsuitable for both natural aquatic ecosystems and drinking, and poor means unsuitable also for agricultural and industrial purposes.

Potential evaporation is calculated on a monthly basis, using the empirical relations of Thornthwaite (1948). Actual evaporation and soil moisture dynamics are calculated according to Thornthwaite and Mather (1955). Net precipitation is divided into two fractions: direct runoff and percolation. Both the groundwater and the surface water store are modelled as linear reservoirs, which means that outflow linearly relates to storage. Each water store is represented by a simple mass balance:

$$\frac{dS(t)}{dt} = \sum F_{in}(t) - \sum F_{out}(t) \qquad (2)$$

in which S is the storage in kg, ΣF_{in} the sum of the inflows and ΣF_{out} the sum of the outflows.

3.4 The impact sub-model

The impact model calculates actual water supply to households, irrigated lands, livestock and industry as a function of demand and actual allocation. On the basis of water use and water availability, the model calculates water scarcity (on a scale between zero and hundred per cent). The water availability in a region is divided into two components: internal and external sources. The first refers to the available amount of water due to precipitation within the region. The second consists of the water flow entering the region from upstream.

Water costs per litre are calculated per sector on the basis of water scarcity and water quality. In addition, the impact model calculates the amount of hydroelectric power generation as a function of the generation capacity and the utilisation fraction, the latter depending on the river runoff.

3.5 The response sub-model

The annual expenditure required to meet a certain water demand is calculated as the product of the demand and the costs per litre. Expenditure needs are calculated separately for the domestic, irrigation, livestock and industrial sectors. In a similar way, the model calculates required expenditure for sanitation, hydropower, and domestic and industrial wastewater treatment. Actual expenditures are a function of required expenditures and actual allocation of means. The response model includes a number of policy variables - in the form of 'manageable' parameters - that can be changed by the user of the model. The maximum expenditure for a certain sector, expressed as a fraction of the gross national product, is such a policy variable. Other policy variables in the model are: the technological development rate (representing the effect of research and development programmes), the diffusion rate (representing the effect of public awareness raising), the ratio between water prices and actual costs (water pricing policy), and export of water to another river basin.

3.6. Representation of the four perspectives

The model has been built in such a way that the user can apply different perspectives on how the system behaves (world-views), on how the system is or should be managed (management styles) and on how external factors will develop (contexts). For that purpose, different perspective-based model formulations and different input values are available (Table 1).

The hierarchist context is largely an extrapolation of current trends. The egalitarian context is characterised by more modest growth rates. The individualist context represents a future of rapid economic growth. The hierarchist world-view regards the world as stable within certain limits. The egalitarian world-view considers the world to be vulnerable to perturbations. Within the individualist world-view, the world is relatively robust. The hierarchist management style is aimed at control and regulation, the egalitarian management style at prevention and the individualist management style at adaptation. The fatalist management style is passive, which means that effectively no measures are taken. The user of the model can get an insight into the risks of a particular management style by varying the world-view and context while keeping the management style constant.

4 Results

The integrated approach has resulted in a number of interesting insights. Both the global water study and the Zambezi study show that the interaction between mankind

Table 1. Basic assumptions per perspective

	Hierarchist	Egalitarian	Individualist	Fatalist
Socio-economic context				
Economic growth	Medium	Low	High	-
Population growth	Medium	Low	High	-
Increase of total cropland area	Medium	Low	High	-
Increase of irrigated cropland area	Medium	Low	High	-
Hydropower development	Medium	Low	High	-
World-view				
Driving forces water demand	GNP, technology	GNP, water price, technology	GNP, water price	-
Indicator of water availability	Stable runoff	Stable runoff	Total runoff	-
Indicator of water scarcity	Consumptive water use / stable runoff	Total water supply / stable runoff	Consumptive water use / total runoff	-
Growth elasticity water demand	Medium	Low	High	-
Price elasticity water demand	Zero	Low	High	-
Ratio consumptive water use / total use	Medium	High	Low	-
Water supply costs	Increase moderately	Increase rapidly	Increase slowly	-
Desalination costs	No change	No change	Decrease	-
Ice sheet sensitivities	Medium	High	Low	-
Critical temperature increase glaciers	Medium	Low	High	-
Management style				
Inter-basin water trade	Medium increase	Zero	large increase	Zero
Technological diffusion rate[1]	High	Low	Zero	Zero
Technological development rate[1]	High	Low	Zero	Zero
Percentage water price / actual cost	Increase to 75%	Increase to 110%	Increase to 100%	No change
Use of water sources	No change	Less groundwater use	More desalination	No change
Artificial groundwater recharge	Increase	Zero	Increase	Zero
Public water supply coverage	Realistic policy targets	Ambitious policy targets	Depending on GNP per cap.	No policy targets
Sanitation coverage	Realistic policy targets	Ambitious policy targets	Depending on GNP per cap.	No policy targets
Fraction of wastewater treated	Realistic policy targets	Ambitious policy targets	Depending on GNP per cap.	No policy targets

[1] These parameters refer to (non-price driven) improvements in water-use efficiency.

and water is gradually changing. This change is described as the 'water transition', consisting of three phases. In the first phase, a continuing development of new water resources takes place, to provide water to an increasing number of people and to increase yields in the agricultural sector. The second phase is characterised by growing water scarcity and competition between different water users, which slows down the rapid growth in water demand. In the third phase water scarcity has reached a level at which people are forced to use water more efficiently and to reduce pollution. Each phase requires its own type of water policy, which implies a shift from supply towards demand policy. Making this move can be a problem, but a greater problem can arise if disagreement exists about the exact current phase and thus about the necessity for change.

The individualist perspective, which typically correlates with the first phase of the water transition, cannot only be found in developing countries, where ample possibilities for growth might be presumed, but also in industrialised countries, where continued growth is assumed to be possible through the use of new techniques and through increasing efficiency. The hierarchist perspective, which agrees with the second phase of the transition, can also be found all over the world. According to this view, people have to balance the desire for further growth with physical, societal, economic and technological limitations. The egalitarian perspective, pertaining to the third phase of the transition, is also represented everywhere to a greater or lesser extent. The large differences between the three perspectives leave room for the fatalist perspective, according to which people cannot do other than await and cope with future developments as well as possible. Depending on the dominant perspective at a certain moment in a particular region, people will aim for a specific type of water policy, corresponding to the phase in which people think they are. From the individualist perspective, strong policy interference is not necessary, because there is a self-regulating mechanism: water demand and supply grow as a result of socio-economic development, which in turn is supported by an increasing exploitation of the water system. The most important aim of water policy should be to guarantee a proper functioning of the water price mechanism. According to the hierarchist perspective, increasing government interference is unavoidable, to be able to meet the different demands. For instance, governments would have to stimulate large-scale water resources projects and promote wastewater treatment. Water subsidies fit within the objective of adequate water supply for all. From the egalitarian perspective, it is considered most appropriate to charge full water costs to the consumer, even adding a water tax, to help slow down increasing water demand as much as possible. In addition a task of governments would be to increase people's awareness of the effects of profuse water use. In the fatalist perspective the type of water policy does not really matter, which means that there will be little active water policy.

A risk analysis of the different policy strategies shows that the fatalist management style generally carries the highest risks. Criteria which are used in this evaluation are for instance: what are - under varying context and world-view - the expected long-term consequences of the strategy on water scarcity, public water supply, wastewater treatment, and required expenditure in the water sector. In the Zambezi basin, the egalitarian management style carries lower risks than the hierarchist or individualist styles. This can be understood through the egalitarian emphasis on demand policy. In the global water study, the differences between the hierarchist, individualist and egalitarian management styles are less pronounced. However, it has become clear that a number of elements from the egalitarian management style would deserve attention if one were to aim at excluding high risks. In particular the water-pricing policy preferred by the egalitarian fits within a strategy of risk avoidance. Subsidies for water would be allowed only if people would not be able to afford clean fresh water otherwise, which applies to public water supply to the poorest only.

A surprising conclusion from the global water study is that the loss of fresh ground water as a result of groundwater withdrawals might be a significant driving force behind sea-level rise. The contribution of groundwater losses to sea level rise in the past hundred years is estimated at 35-45%. For the coming hundred years, this contribution is estimated at 25-45%. This finding - based on the full set of 36 experiments carried out - contradicts current opinion as embodied in the latest IPCC reports and deserves closer examination. This conclusion is supported by for instance Sahagian *et al.* (1994).

A result of the Zambezi study is an assessment of the risks attached to the so-called 'Harare priorities', a set of water policy priorities that came out of a workshop in Harare in November 1996 (UNEP, 1996). It is shown that applying these priorities throughout the basin will support development in the region effectively in only one out of the nine possible futures that might evolve (varying context and world-view under a given management style gives $3 \times 3 = 9$ scenarios). Development will be supported sufficiently, but with some trade-offs (like high vulnerability to drought and inefficient water use) in six out of the nine possible futures. In two scenarios, the Harare priorities will work out very ineffectively, where water supply will fall short and where incredibly high investments in the water sector would be needed. These findings show how one can use the concept of risk to evaluate intended policy and in this specific case, they might trigger the search for a strategy with a lower risk profile.

5 Conclusion

The results show that an integrated research approach can lead to fresh insights with regard to the interaction between socio-economic developments and changes within the water system. This approach can help in assessing the relative importance of the different processes involved in this interaction. The use of perspectives can be helpful in making the greatest uncertainties explicit and in estimating the risks of different policy strategies. Information about risks of policy can be relevant to policy makers in setting policy priorities.

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