Working Paper

Climatic Change Impact on Water Resources - a Systems View

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WP-93-30
June 1993

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Abstract

Global climate change related to natural and anthropogenic processes has been the topic of many research projects and high-level debates. Despite the ongoing research efforts, the climate predictions cannot be rated any better than speculative or possible scenarios whose probability of occurrance is, at the present stage, impossible to assess. One of the most significant impacts of the "greenhouse effect" is anticipated to be on water resources management, including different elements of the hydrologic cycle, water supply and demand, regional vulnerability, and water quality. Thus, the impact of climate change appears to be an additional component on top of the large number of stressing (existing and likely future) water related problems.

The existence of the greenhouse effect, the increase of greenhouse gas emissions, and the rise of corresponding concentrations are certain things. However, impacts become increasingly uncertain as we move towards hydrology and water management. For this analysis, we would need information on much smaller spatial and temporal scales (i.e. a basin, a subbasin, or an agglomeration and the duration of rare, short-lasting events, such as floods, droughts or low flow periods) than used in climate studies.

The objective of the present paper is to analyze the climate change impact on water resources from a systems view, to discuss scientific gaps, and to identify the possible future role of IIASA in this subject area.

The report discusses the role of different scales and uncertainties, as well as the hydrological perspective of global circulation models. An essential part of the analysis is devoted to the impact of climate change on the hydrologic cycle and water resources. Subsequently, our preparedness for probable global (climate) change is discussed in terms of assessment, planning, design, adaptation, and others. The focus is obviously on water-related response strategies. Finally, the paper identifies four challenging future research areas for IIASA as follows: (1) Central Europe as a case to study climate change impacts on water resources management; (2) The application of a pre-hydrological model to probabilistically assess the rainfall pattern of a river basin; (3) Methodological research to study water management vulnerability with a strong focus on uncertainties (including methods and concepts such as the Delphi technique, Bayesian statistics, reliability resilience, vulnerability, robustness, and surprises); and (4) The impact of climate change on water quality.

Climatic Change Impact on Water Resources - a Systems View

*Z. Kundzewicz**
*L. Somlyódy***

1 Introduction

Climate is typically understood as the representative ensemble of weather conditions over a longer time period, that is, an aggregate term smoothing the weather variability. It is characterized by a number of variables like temperature, precipitation, and wind velocity.

Global climatic change related to natural and anthropogenic processes has been the topic of high-level debates. The problem is sometimes ranked as one of the most important ones for the forthcoming century. The proliferation of climatic change information can be noted in the media and the number of books on the subject area is mushrooming. The public is kept informed about recent predictions and impact assessments. All of these happen although the predictions are highly uncertain. Despite ongoing research efforts the predictions cannot be rated any better than speculative, at most as possible scenarios, whose probability of occurrence is, at the present stage, impossible to assess.

Part of the public, including several established scientists, suggest that the likely changes could be beneficial at the local scale. Vineyards in Britain, pleasant water temperature in the Baltic Sea, longer vegetation season, fewer frost days (less energy demand for heating), or warmer Siberia belong to these welcome scenarios. However, it seems that the prevailing part of the scientific community and broad public are seriously concerned about the possibility of climatic change and its impacts. Nations have adapted themselves to definite and stationary climatic conditions. Any change would destroy the fragile balance resulting from the long-lasting adaptation. It may touch, first of all, the areas which are vulnerable nowadays. It would trigger the need for a costly, and long-lasting process of adaptation to the changed conditions.

The objective of the present report is to put the climatic change impact on water resources into a systems view, i.e. to systematize the scarce certain information, and to account the existing strong uncertainties. A holistic cradle-to-grave perspective is followed, where individual links of the reasoning chain are examined. A discussion of scientific gaps, and their possible reductions, prospects for research and rationale for decisions and actions is offered.

It seems worthwhile to comment on the very notion of uncertainty, as it is of primary importance in this contribution. The notion of uncertainty can be understood in quite a broad sense (Kundzewicz, 1993). The meaning of this term may range from the state of being unknown indefinite, indeterminate, on one extreme, to minor uncertainties about the value of perfectly certain parameters (trivial uncertainty, such as whether a parameter has the value 0.76 or 0.77). In the climatic change studies one encounters strong uncertainties related to the lack of understanding of complex feedback mechanisms which control the processes. As a result, one can hardly conclude even the direction of change.

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The possible future role of IIASA in this subject area is also discussed in the present contribution. Research into the water component of climate change has been conducted at IIASA for several years. Formulation of a sound and timely scientific program addressing the issues of importance to the international scientific community is not only an intellectual challenge, but also the question of developing an attractive research program for an international scientific institute at the same time. Several components of possible research at IIASA into climatic change impact on water resources are presented. One of the avenues is the development of a methodology for blending information from different sources, typically of different qualities. A need for a systematic procedure for using expert judgments is felt. Furthermore, it is necessary to develop an updating apparatus enabling one to incorporate the growing understanding, better prognostications, and the new observation results into the assessment and decision schemes. Another possible area would be the multi-criteria framework for assessment of unsatisfactory system behavior. Such criteria as reliability, resilience, vulnerability, and robustness, which had been pioneered at IIASA, have gained worldwide recognition. There is a definite need to aid in translation of these notions, which are colloquially formulated, into the language of practice of water resources management - decision and design.

2 Features, Scales and Design Conditions of Water Resource Systems

Seventy-one percent of the area of the Earth is covered with water. However, despite this apparent abundance of water at the global scale, the availability of water on land is far from being uniform. There are well defined climatic zones with differing average water availability; arid and semi-arid areas of rainfall deficit, and humid areas of rainfall surplus.

Vast amounts of water are needed to sustain life on Earth and virtually all areas of economic activity. Domestic water use in European countries is, on average, of the order of 150 liters per capita per day. In order to produce one kilogram of corn, rice, and cotton, a few hundred, few thousand and some twenty thousand liters of water are needed. Water use in industry depends strongly on the technology used and can vary as much as 1 to 40, for a unit of product, between old and new (water saving) technologies.

The problem of access to adequate and safe water supply is far from being solved at the global scale. There are over one thousand million people in less developed countries, who do not have adequate water supplies. Estimates of the number of people affected with water related diseases are of the same order.

Humankind has always been faced with the problems of having too much or too little water. The former case, known as floods, have devastating effects and count as major natural disasters, that have caused and still continue to cause, high losses in lives and property. Floods are of pronounced, violent character, and are therefore more spectacular than significantly more long-lasting droughts. The notion of this latter plague is definitely more complex, but the devastating effects exceed by far those of all other natural phenomena. It is expected that the greenhouse effect may have impacts on hydrological extremes such as floods and droughts, influencing all their parameters - severity, frequency, and intensity. Several acute events of this type have occurred recently. Increased winter precipitation (rain, rather than snow) would cause a rise in winter flood danger, whereas increased evapotranspiration in the vegetation season caused by temperature rise may lead to soil moisture deficits, agricultural, ecological, and hydrological droughts.

Kulshreshtha (1993) analyzed regional water-related vulnerabilities considering, apart from possible climatic change, also population growth scenarios, and policies related to food self-sufficiency. He predicted that the present vulnerabilities are likely to aggravate in the decades to come. Most vulnerable regions now are in countries in Northern Africa and the Middle East. The projection of Kulshreshtha (1993) predicted a number of new vulnerabilities in many regions, for instance Southern and Central Europe. However, already now water availability in the countries of Central Europe can locally be the impediment of growth. Moreover, even the scanty water resources in these countries are effectively reduced due to the quality dimension. The water bodies are still recipients of all sorts of pollutants. The potential danger of increasing water stress in the countries of Central Europe has been signalized in several publications worldwide already for decades, cf. The Global 2000 (1980).

A typical scale of concern in hydrology and water resource considerations is the one of a drainage basin. However, the notion of drainage basins itself covers a variety of spatial scales. It ranges from a micro-basin (a portion of a square kilometer) of a smallest first-order stream that receives no tributaries to large, continental-scale river networks, covering millions of square kilometers. A classical scale of hydrological analysis refers to a moderately steep and homogeneous catchment in a temperate or humid climate, within the rainfall-runoff framework. However, hydrological systems are highly heterogeneous. For example, hydrogeological parameters may change by several orders of magnitude within the area of an experimental plot. Therefore, even at the small hydrological scale, models require a great deal of idealization (e.g. taking effective values for naturally heterogeneous, spatially and temporally variable, elements; neglect of several inter-connections). The typical scale of a water management problem is a basin, a subbasin, a region, or an agglomeration.

Although the mean values of hydrological variables are of high importance, essential are also extremes, i.e. the characteristics of tails of distributions, applicable to rare events which may have profound impacts. It is the characteristics of rare events, of local relevance to the site examined, that are explicitly used in design standards (e.g. 100-years flood, 7-days-10-years low flow, or the flow exceeded in 355 days of a year, as frequently employed as a design criterion for point source related water quality problems). Such notions which have been meaningful under the assumption of stationarity are questionable in the nonstationary environment. Probability-based design pertains to such local works as bridges, levees, dams, spillways, and water supply systems.

The temporal scale of concern in hydrology and water resources does also vary greatly, depending on the aspect in question. The temporal scale, in the sense of duration of distinctly distinguished states of hydrological variables, may range from minutes (floods on small rivers) to years (prolonged droughts). Such processes as erosion, soil impoverishment, and nutrient transport, agricultural and urban non-point source pollution, are typically associated with short-lasting events of high magnitude. That is, on a small watershed, the bulk of the annual transport may occur during an intensive storm lasting minutes.

One can conclude that studying the climatic change impacts on water resources, it is necessary, irrespective of the methodology used, to provide adequate notion of the spatial and temporal scales, which are of relevance to hydrological processes.

3 Certainties and Uncertainties

Climatic change problems are often formulated in neat flow charts appealing to system specialists. It seems natural to try to analyze the certainties and the uncertainties in these flow charts (Fig. 1).

There has been significant natural variability of climate observed or recognized over several large time scales - decades, centuries, millennia, etc. The sceptics say the climate has been continuously changing all the time. It has changed abruptly so many times before, so it might change again. This time, however, the man-induced mechanism is being identified, that could be a potential reason for change.

There are so very few things that we know for certain in the climatic change studies and so many things based on one's belief rather than on rigorous scientific evidence. What do we know for certain? There are three essential facts:

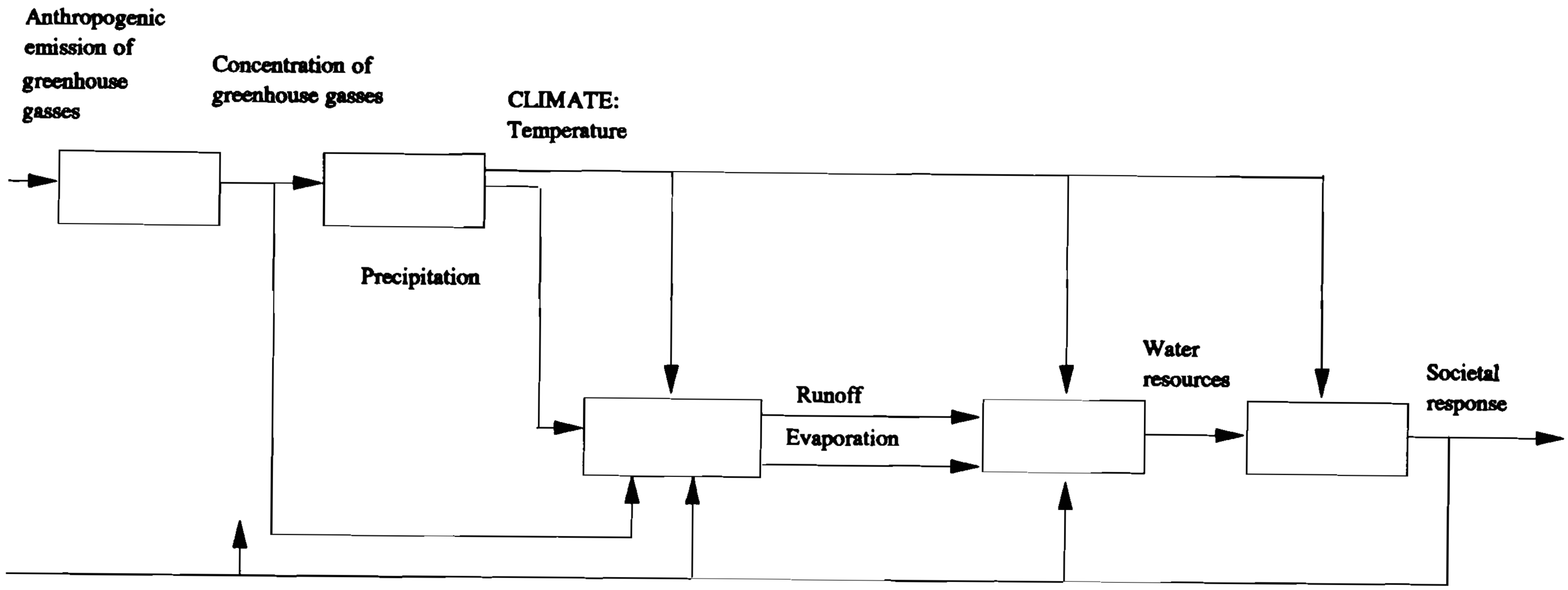


Fig. 1 Climatic change versus water resources: from burning fossil fuels to societal response

First, The greenhouse effect exists. No doubt about that; without it the planet Earth would be significantly cooler. The greenhouse effect means that the atmosphere has transmission properties for shortwave radiation and absorption properties for longwave radiation. That is, longwave radiation emitted by the Earth is trapped by the greenhouse gases in the atmosphere and contributes to the global warming. Greenhouse effect theory works well also for other planets of the Solar System, where the composition of atmospheres and the distance from the Sun explain the thermal conditions.

The second certain thing is the ever increasing man-induced emission of carbon dioxide and other greenhouse gases. Increasing combustion of fossil fuels has been found to be a necessary condition of economic growth.

The third certain thing is the rise of concentration of greenhouse gases in the atmosphere. It is not, however, the direct logical conclusion from the former paragraph, although common sense says that the rise of CO_2 emission, and also large-scale deforestation, i.e. removal of a carbon sink, should cause a rise in CO_2 concentration in the Earth atmosphere. However, fossil fuels give just a few (slightly over three) percent of the global annual carbon fluxes, i.e. far less than the primary productivity of terrestrial ecosystems and of the ocean. The global carbon system contains inter-connected carbon sources and sinks, whose behavior is not yet well understood. Therefore, in view of the complexities, uncertainties, and the lack of understanding, the hypothesis on the cause of the rise of CO_2 concentration needs to be proved by real data. Such observational evidence exists, thus increased CO_2 concentration in the atmosphere is the third certain fact. The observational material collected at Mauna Loa (Hawaii), far away from the main centers of pollution, over the last three decades is very persuading (Keeling et al., 1989), though even this series is questioned by some researchers. Unambiguous and dynamic rise of CO_2 concentration in the atmosphere can be detected by rigorous statistics, but also with bare eyes. Strong growth of atmospheric concentration has been also observed in other greenhouse gases (IPCC, 1990) like methane, chlorofluorocarbons, nitrous oxide, and ozone, which are collectively about as important as carbon dioxide.

However, the above three observations complete the set of clear and straightforward, unanimously accepted evidence on global climatic change.

The next piece of the logical chain is the dilemma, whether or not temperature rise has been observed already. The global temperature record over the last hundred years shows some rising trend (around 0.6° rise). There are, however, strong departures from this rising tendency. There was a strong, dynamic warming in the 1920s and 1930s and subsequently quite a distinct cooler phase extending for three decades up to the early 1970s. The prophecy of global cooling was raised then in the mass media and in thriller books. Occurrence of three cooler decades, and the difficulty with unambiguous detection of warming by rigorous statistics made several scientists question the available instrumental temperature record as a proof of on-going climatic change. There have never been so many natural variabilities of the Earth climate, observed at different time scales. Schneider et al. (1990) state that "[i]t is still possible that the observed trend and the predicted warming could be chance occurrences. There is no objective way to assign probability to that chance ...". However, Schneider, one of the authors of the latter reference, "intuitively believes it to be of the order of 25%".

How long will we wait until a persuading evidence arrives? "Another decade or two of observations of trends in Earth's climate and its forcing functions ... should produce signal-to-noise ratios sufficiently obvious that almost all scientists will know whether present estimates of climatic sensitivity to increasing trace gases have been predicted accurately or not" say Schneider et al. (1990).

A significant increase in fossil fuel combustion has been noted. However, when it comes to predictions of this process, a considerable uncertainty occurs. What is going to be the future trend of the emission of greenhouse gases? What option will be taken by humankind? What are going to be the effects of the phase lag? Even if emissions of all greenhouse gases end today, their concentrations in the atmosphere (and hence the temperature rise) would continue to grow. This inertia, or thermal delay, is a typical property of a response of a dynamic system, yet is difficult to quantify. The phase shift may be equal to a value from the range 10 – 100 years.

Water vapor, although not mentioned yet, is by far the most important of the greenhouse gases and may become, through feedbacks and interconnections, the decisive factor in the climatic change. Under these circumstances, understanding of the detailed physical, chemical, meteorological and hydrological mechanisms of the fate of water vapor is of utmost importance.

There is, therefore, a great deal of uncertainty in the forecast of changes in temperature and in precipitation expected in the decades to come. The changes may vary substantially for different areas and for different seasons of the year. But, even for the same area and season, the predictions made by different groups of analysts largely differ. There are high uncertainties related to regional prognostications of temperature and both global and regional forecasts of precipitation. The uncertainties grow as one goes down the spatial and temporal scale, e.g. from global to regional scales, and from annual to shorter time periods. The reasons for uncertainties will be explained in the sequel. There are gaps in understanding and a definite lack of the data base required.

Further strong uncertainties regarding the passage from hydrology to water resources and their management result from the need to forecast future water demand. This is conditioned by a number of unpredictable factors, like population growth, economic growth, agricultural policy, land use changes, and technological innovations. Finally, there are vast uncertainties about the societal response to the new situation.

The elements of the logical diagram shown in Fig. 1 pertain to different scales of perception. Anthropogenic emission of greenhouse gases is essentially local. It is aggregated into atmospheric response around the globe. The climatic predictions are offered through a widely spaced grid and have to be used at the essentially smaller scales of relevance to water resources, i.e. individual catchments (again on the local or regional scale). Further, societal response is another larger-scale element of the diagram.

It is necessary, however, to see the eventual climatic change consequences in the perspective of other global processes which are occurring. There is a substantial rise of population of the globe forecasted for the decades to come. Nations and individuals have growing development aspirations, as far as living standards are concerned. This will put severe pressure on the environment. There is a common recognition that the anthropogenic, man-induced changes which have occurred in the recent past have no similarly fast counterpart in history. This statement, however, cannot be rigorously proved - we cannot credibly decipher the details of the dynamics of processes from the very remote past.

4 Global Circulation Models - a Hydrological Perspective

Global Circulation Models (GCM) are the way to describe the complex large-scale processes with the help of elegant equations of mathematical physics. Although the basic equations used (expressing the laws of conservation of mass, momentum, energy, and the ideal gas law) have been known for many decades, it is only quite recently, in the era of advanced computer technology, that this formidable computational task could be undertaken at the global scale. Computation of GCMs require the fastest and most powerful computers available (so called supercomputers) in order to accommodate many spatial points in three dimensions. The results are given in the temporally aggregated form in most cases.

Recent computer technology makes it possible to run global circulation models, but the calculations can proceed only for widely spaced points of the spatial grid, at and above the Earth surface. Giorgi & Mearns (1991) presented the computer power needed for a given resolution on the Cray X-MP supercomputer. A global grid with a resolution of 4.5° latitude by 7.5°

longitude (i.e. ca. 500x600 km grid cell size at 40° latitude) would require about 1 minute of central processor unit (CPU) use for a one-day simulation in 30 minutes time steps. However, the above wide spacing of GCM resolution is definitely too crude for the hydrological and water resources context. Essential processes occur over far smaller scales than the above. Therefore a need for higher resolution comes about. However, going to a resolution of 0.3° latitude by 0.3° longitude (i.e. ca. 30x30 km grid cell, or 900 km^2) with time steps of 1.5 minutes would require about 3000 minutes time for a one-day simulation. The latter fine spatial resolution has not been run yet, actually, as over two days computing time would be necessary to simulate a day of climate (cf. Giorgi & Mearns, 1991). However, even the latter resolution clearly demonstrating the misfit of scales would be hardly sufficient in addressing several hydrological problems. It would mean that a medium size catchment with an area of a few thousand square kilometers would be represented by a couple of nodal points of the GCM computational grid. As stated by Schneider et al. (1990), "no computer is fast enough to calculate climatic variables everywhere on the earth and in the atmosphere in a reasonable time". And, further - "within the foreseeable future even the highest resolution three-dimensional GCMs will not have a grid much less than 100 km".

How good are the GCMs? The specialists rate them in terms of the justification of assumptions taken and the adequate representation of processes. They analyze whether idealized or realistic geography, none or realistic topography was used, and whether or not the annual/diurnal cycles were accounted. The rating involves the spatial resolution and the way in which the ocean/sea ice elements were considered. However, "the final proof of the pudding is eating it", rather than analyzing the set of ingredients and the way of cooking. Therefore, the ultimate criterion of goodness of GCMs is not so much the soundness of their theory, but rather the accuracy with which they can reproduce the real data. Although the data for future scenarios do not exist, there have been several tests for GCMs, measuring their fit to the available records related to the past and to the present. The goodness of reproduction of the present-day climate is perhaps the most obvious test (e.g. reconstruction of zonal regularities). Then comes evaluation of the fit to the data series of the instrumental period (say, last hundred years). Finally, it is interesting to examine how GCMs cope with the reconstruction of the paleoclimates, i.e. reproduction of the data on the remote past that have been deciphered from proxy records.

There have been both moderate successes and essential failures noted while testing the available GCMs. Successes mean that the gross features of present temperature distribution over the globe are represented rather well. There are, however, considerable discrepancies between the more regional information produced by the GCMs and the results of observations, which is rather intuitively expected considering the large grid spacing. Many details of the present-day climate at the regional scale are reproduced completely falsely, and apparently the models at their present stage of development are incapable of giving reliable practical (i.e. smaller-scale) results. The lack of agreement in performance of atmospheric GCMs in terms of their simulation of precipitation calculated for the present conditions as compared to the observed record, in the zonal presentation, is shown in Fig. 2 (source: Gates, 1985). It should be noted, however, that some progress has been achieved, and the large discrepancies between models results tend to decrease with time.

There is a substantial quantitative difference between the temperature rise observed in the last hundred years and the ones computed by general circulation models. During that time a 25% rise in atmospheric concentration of carbon dioxide has been observed. The observed value of temperature rise was 0.6°C. The latter result is the state of the art of the reconstruction of temperature, based on hundreds of records, with an attempt to eliminate spatial sampling errors and bias. Most climatic models arrived at a global warming of 1°C, that is, substantially higher. Schneider et al. (1990) gave seven possible explanations of the discrepancy ("litany of excuses"). They believe that "the roughly twofold discrepancy is still not large".

There is a wide range of possible prognostications of the rate of average temperature increase, achieved by different models. R.E. Dickinson and W. Clark (cf. Jaeger, 1988) intuitively and

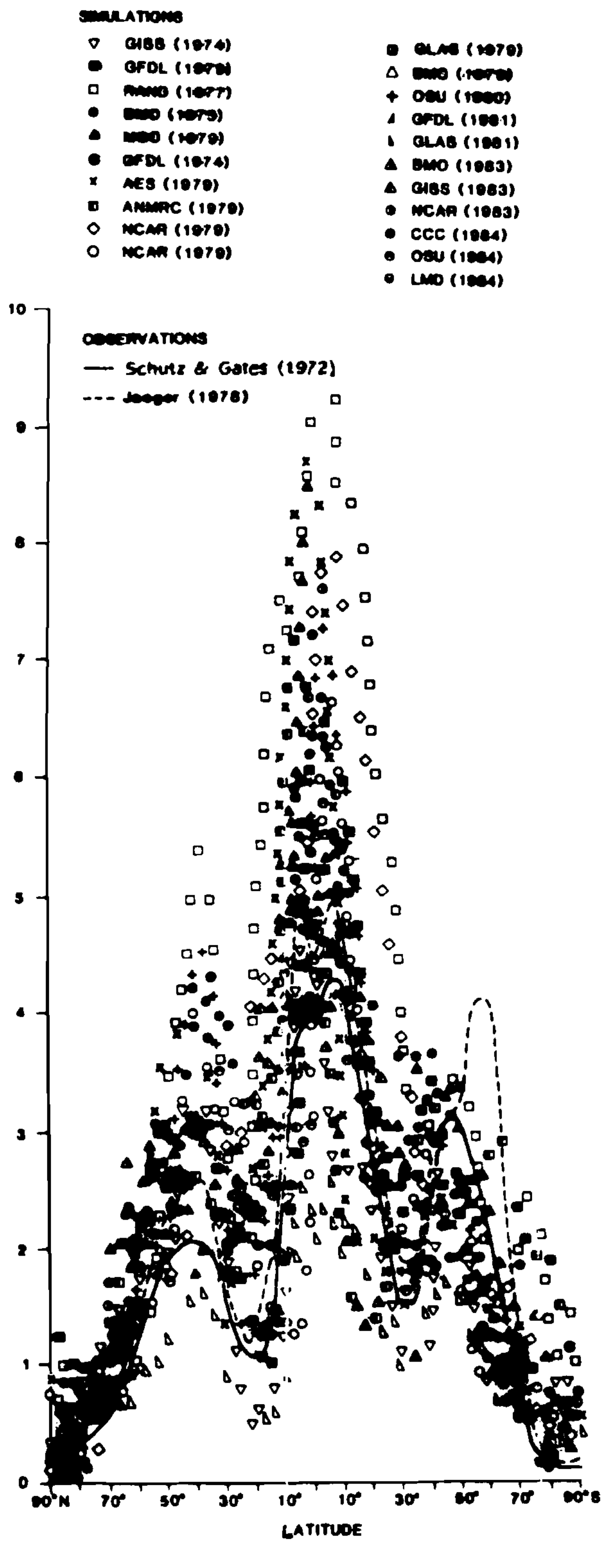


Fig. 2 Performance of atmospheric GCMs in terms of their simulation of precipitation for present conditions as compared to observed ones (after Gates et al., 1985)

subjectively rated the probability at 90 percent that the actual trend would occur within the bounds of 0.06°C per decade and 0.8°C per decade.

As the present climate is not reproduced well, it is hard to believe that the models would work credibly for future climates.

The results of GCMs largely differ on the inter-model basis. A range of predictions of global values of changes in the precipitation and temperature for a $2xCO_2$ scenario is shown in Fig. 3 (data from IPCC, 1990).

Hulme et al. (1990) compared the results produced by five independent GCM experiments for the European continent. The analysis embraced the inter-model comparison of temperature and precipitation in winter and in summer for the $2xCO_2$ and $1xCO_2$ cases. Fig. 4, reproduced from Hulme et al. (1990), shows some detail. Fig. 4a and 4b depict average temperature rise for summer and winter, respectively. Figs. 4c and 4d represent the model-to-model standard variation in temperature rise. Figs. 4e and 4f show the average change in precipitation, and Figs. 4g and 4h illustrate the probability of drop in precipitation. Hulme et al. (1990) stated that for a large part of maritime and western Europe one has "little confidence in the summer precipitation projections ..., so the best model-based scenario would be one of little or no change"! It is a pity that a similar study has not been performed, to the knowledge of the present authors, using a more extensive data base embracing over twenty existing GCMs.

Due to large discrepancies in results it is not uncommon to use several GCM results as possible scenarios in the impact studies. However, there is no obvious rationale for attributing a higher credibility to any one of those. The dilemma emerges of how to choose a GCM to work with if there are several untestable and essentially incomparable models, producing possibly largely differing results at the regional scale. The choice could be dictated by the access conditions, and by personal subjective judgment, that is, degree of confidence.

Analysis of results of several GCMs may end up with a set of discrepant values, prophesying either high rise or high drop in the characteristic of concern, as mentioned further in chapter six.

It could be questioned whether the words "validation" and "verification" are adequate at all in the case of GCMs. Konikow & Bredehoeft (1992) argued that these words are not relevant ("have little or no place") in the groundwater scene. The words "validation" and "verification" could "lead to a false impression of model capability" and "build false confidence into model prediction". Konikow & Bredehoeft (1992) advocated such descriptions as: model testing, evaluation, calibration, sensitivity testing, benchmarking, history matching, or parameter estimation as more meaningful, i.e. shifting emphasis towards understanding of complex systems. In the case of GCMs, the same conclusions could be formulated in a definitely much stronger way. Model testing for past and present conditions was not satisfactory, and performing the check for future conditions is not possible at all.

Schneider et al. (1990) assessed the confidence of projections as high as far as global averages of temperature, sea level, precipitation, and evapotranspiration were concerned. In cases of regional averages, they rated the confidence as low or medium at best. Moreover, they estimated the time for necessary research that would lead to the consensus. They estimated that it will take 0–5 years for the temperature, 5–20 years for the sea level, and 10–50 years in all other cases. On the other hand, IPCC (1990, p. 315) stated that "[t]he time scales for narrowing the uncertainties must be measured in terms of several years to more than a decade". Further, IPCC (1990) expects that essential narrowing of the uncertainties in:

i predictions of the rate of climatic change;

ii predictions of regional differences in climate including water resources (as a result of higher resolution models and a better representation of the hydrological cycle); and

iii predictions and definition of range of possible climate variation (as a result of models containing better representations of clouds, oceans, ice sheets, chemistry and biosphere); would be achieved by 2000, 2005, and 2010, respectively.

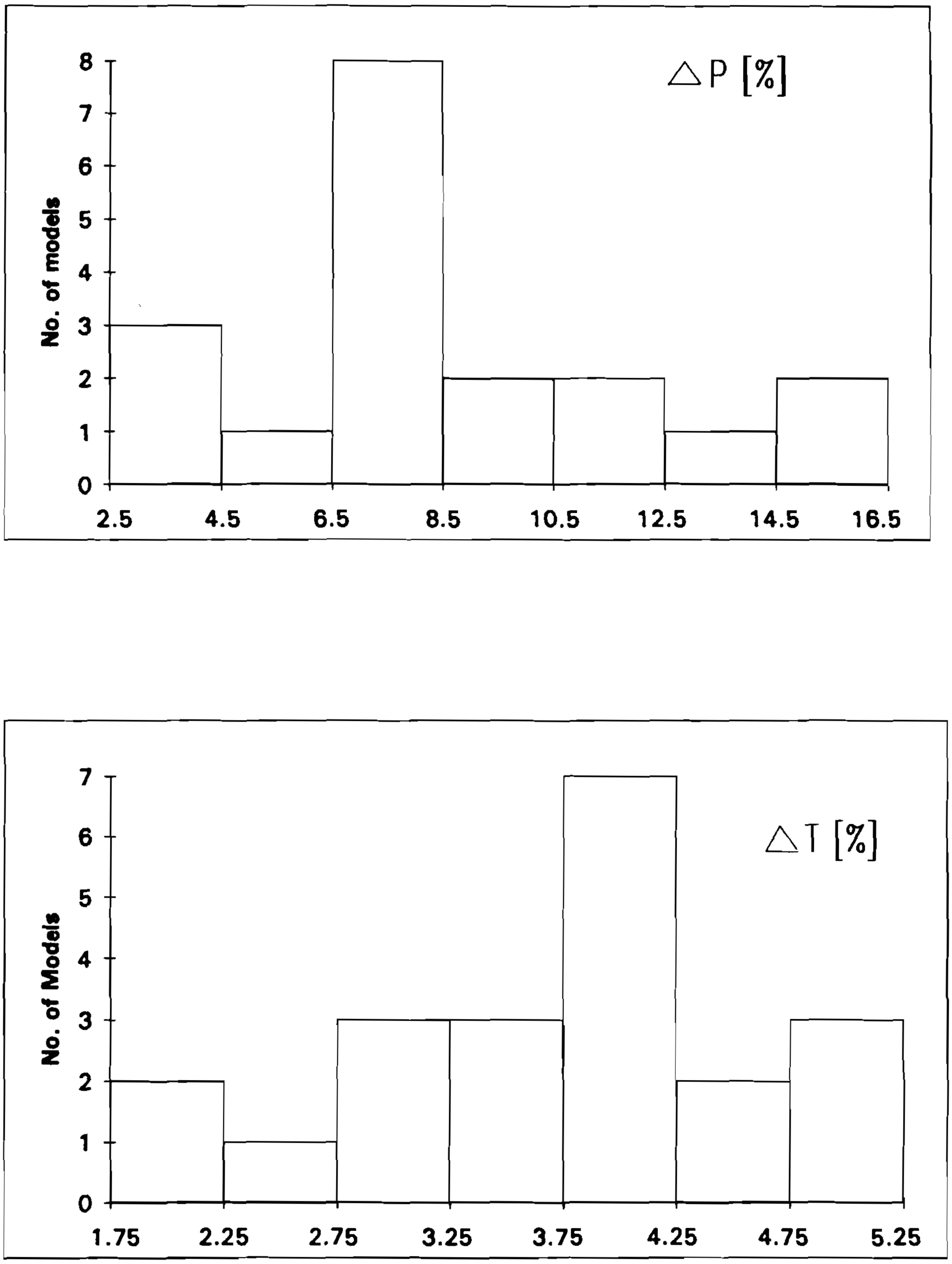
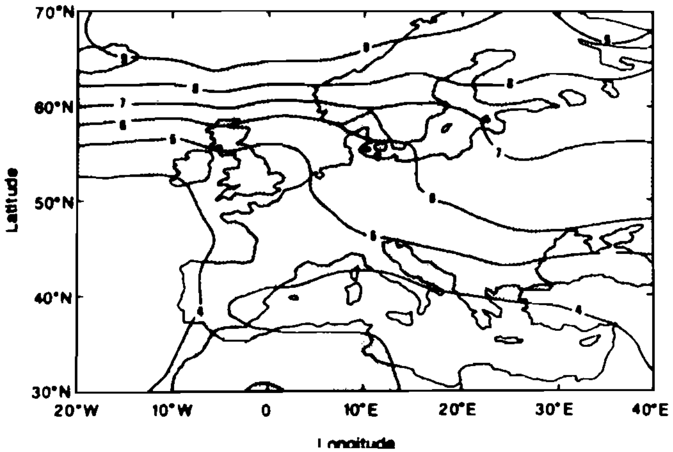
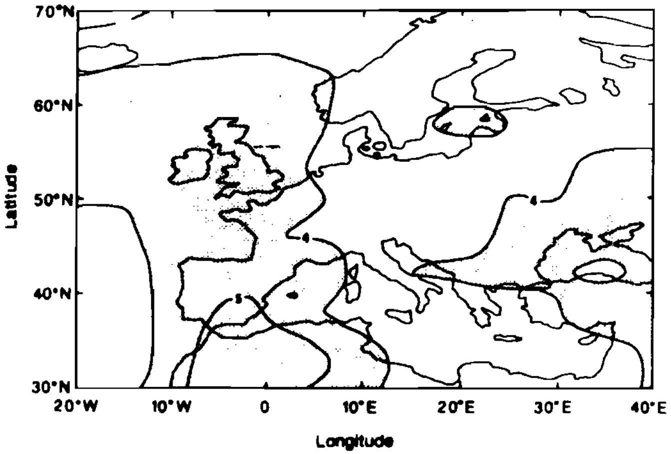


Fig. 3 Comparison of predictions of different GCMs ($2\times CO_2$)
(ΔP – difference in precipitation, ΔT – difference in temperature)

Winter (4a)

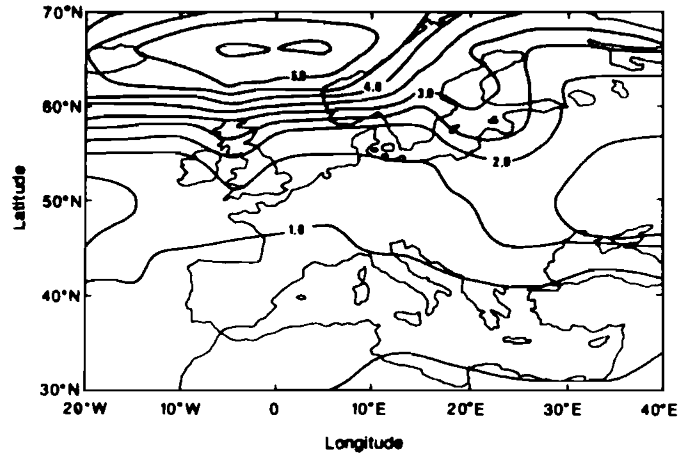


Summer (4b)

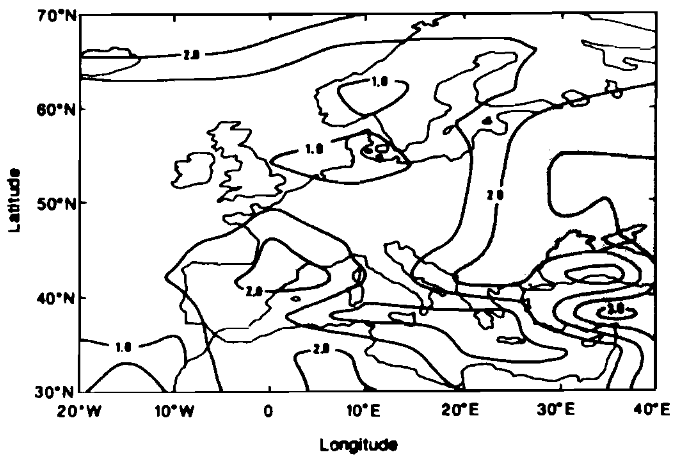


Average change in surface air temperature ($2\times CO_2 - 1\times CO_2$)

Winter (4c)



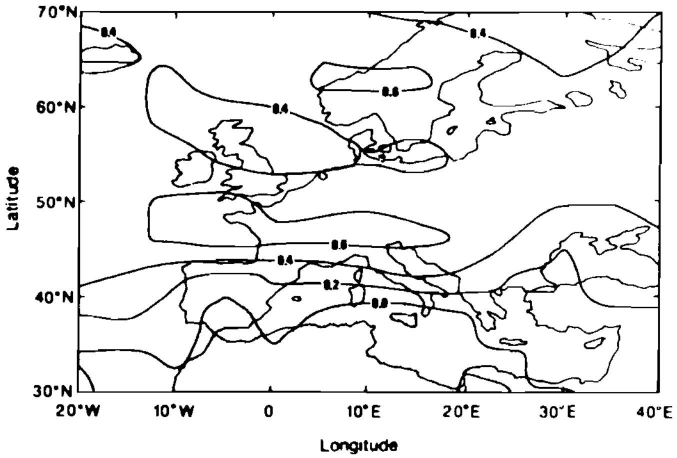
Summer (4d)



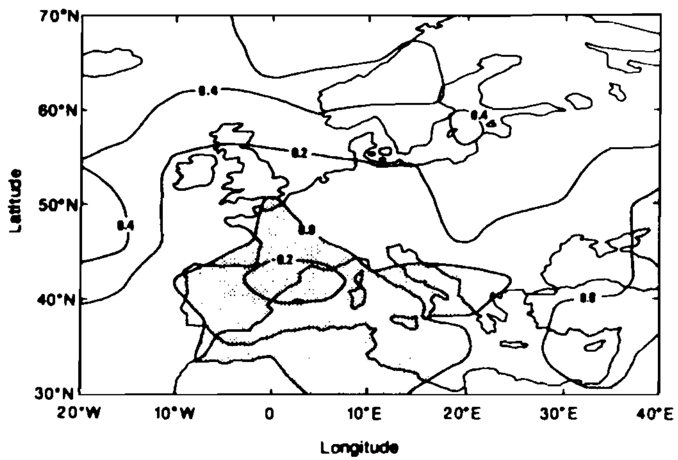
Model-to-model standard deviation of change in surface air temperature ($2\times CO_2 - 1\times CO_2$)

Fig. 4 (a–d) Comparison of results of five GCMs for the European continent (after Hulme et al., 1990)

Winter (4e)

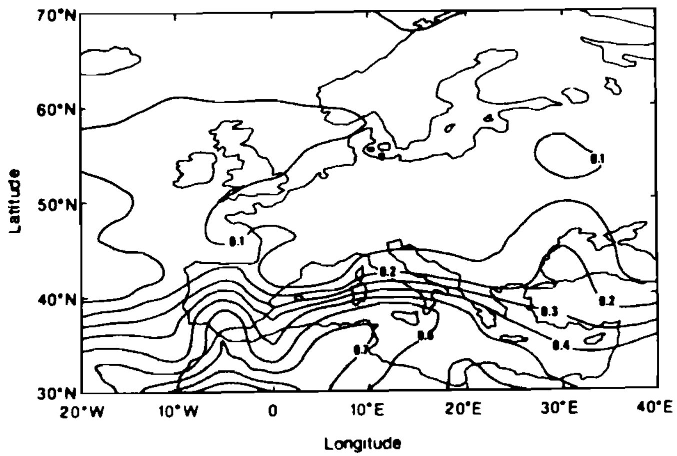


Summer (4f)

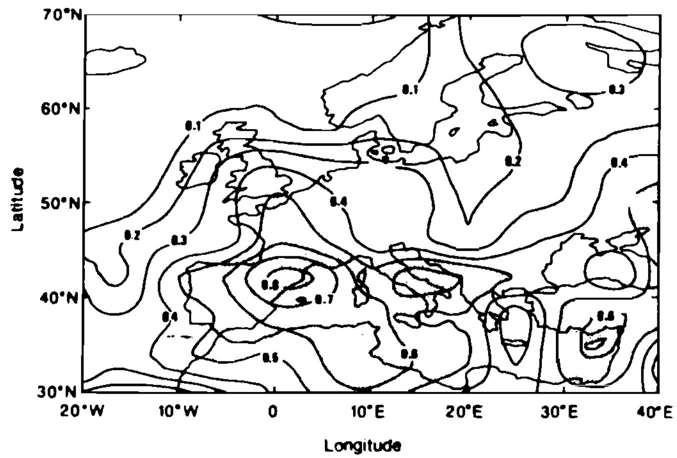


Average change in precipitation $(2\times CO_2 - 1\times CO_2)$

Winter (4g)



Summer (4h)



Probability of decrease in precipitation at $2\times CO_2$

Fig. 4 (e–h) Comparison of results of five GCMs for the European continent (after Hulme et al., 1990)

The issue of narrowing uncertainties will be further commented in Chapter 6.

There are several clear trends of development of GCM technology. One obvious trend is the exponentially growing computer power. Within seven years supercomputers became 68 times more powerful (Verstraete, 1989). Faster and more powerful supercomputers would facilitate developing higher resolution models, thus approaching a more "hydrological" scale of concern. However, as noted by Verstraete (1989), "higher resolution ... models have their own problems ...". They are very expensive and time consuming, as mentioned before. Their climate after longer integration may be even further from reality than that from a lower resolution version, as, in fact "some errors increase while others decrease when the resolution increases" (Verstraete, 1989). Moreover, the higher the resolution, the more severe are the problems with proper setting up of the boundary and initial conditions. There is no way to avoid the parameterization as there are still going to be many processes occurring at far finer scale than the highest resolution practicable. On top of that, the deterministic model structure may be incapable of faithfully reproducing the reality. The use of random components may be required.

5 Climatic Change Impact on Hydrological Cycle and Water Resources

The forecasts announce global warming, whose range is going to be higher at high latitudes. This implies the rise of potential evapotranspiration and thus also higher precipitation, according to the principle of the hydrological cycle - what goes up must come down. Wetter climate in the sense of higher yearly precipitation totals does not preclude the occurrence of significant drop of soil moisture in the summer and reduction of runoff and aquifer recharges. There is a likelihood of increased extremes, i.e. changed frequencies of very dry and very wet spells. The seasonal distributions could be adversely affected. Higher winter precipitation is likely to cause higher floods. Less water in vegetation season is likely to manifest itself in prolonged and more severe droughts, which would significantly and adversely affect agriculture. Prognosticated sea level rise would require very costly protection works in low areas. Warming implies also a drop in snow cover and number of frost days.

Possible climatic change affects virtually all natural processes; all elements of the hydrological cycle. This happens by several means, either as a direct effect of increased concentration of carbon dioxide (stomata openings, evapotranspiration, leaf-area-index, interception, albedo), or as a result of changed temperature and precipitation. However, translation of changes in temperature and precipitation provided by widely spaced GCM prognostications into changes in other variables and processes involved in the hydrological cycle (runoff, infiltration, groundwater flow, evapotranspiration, etc.) at a meso-scale is very difficult. Changed redistribution of energy fluxes and changes in the water cycle induce variations of other related matter cycles, in which water plays the role of a carrier and a solvent. This leads to changes in water quality of surface and subsurface waters alike, irrespective of whether we can consider traditional components such as carbon, nitrogen and phosphorus, or also include, for instance, heavy metals. The statement is particularly true in current times, as we observe the necessary role of diffuse pollution and interactions among various elements of the biosphere, even from the viewpoint of water quality management (see, e.g. Somlyódy et al., 1992).

Any natural cycle can be represented as a flow diagram of inter-connected boxes (Fig. 5). Boxes stand for storages, while links between them represent fluxes. Virtually all boxes and all links shown in Fig. 5 would be subject to changes under the climatic change. That is, both stored volumes and dynamics of water transfers may change in a complicated way, varying both in space (regions) and in time (seasons). Perhaps the local changes could go as far as to modify the structure shown in Fig. 5, making some processes negligibly small.

However, if the global and even regional averages (i.e. the results of the climate modeling endeavors) were perfectly reliable, they would be inadequate for assessing hydrological and water

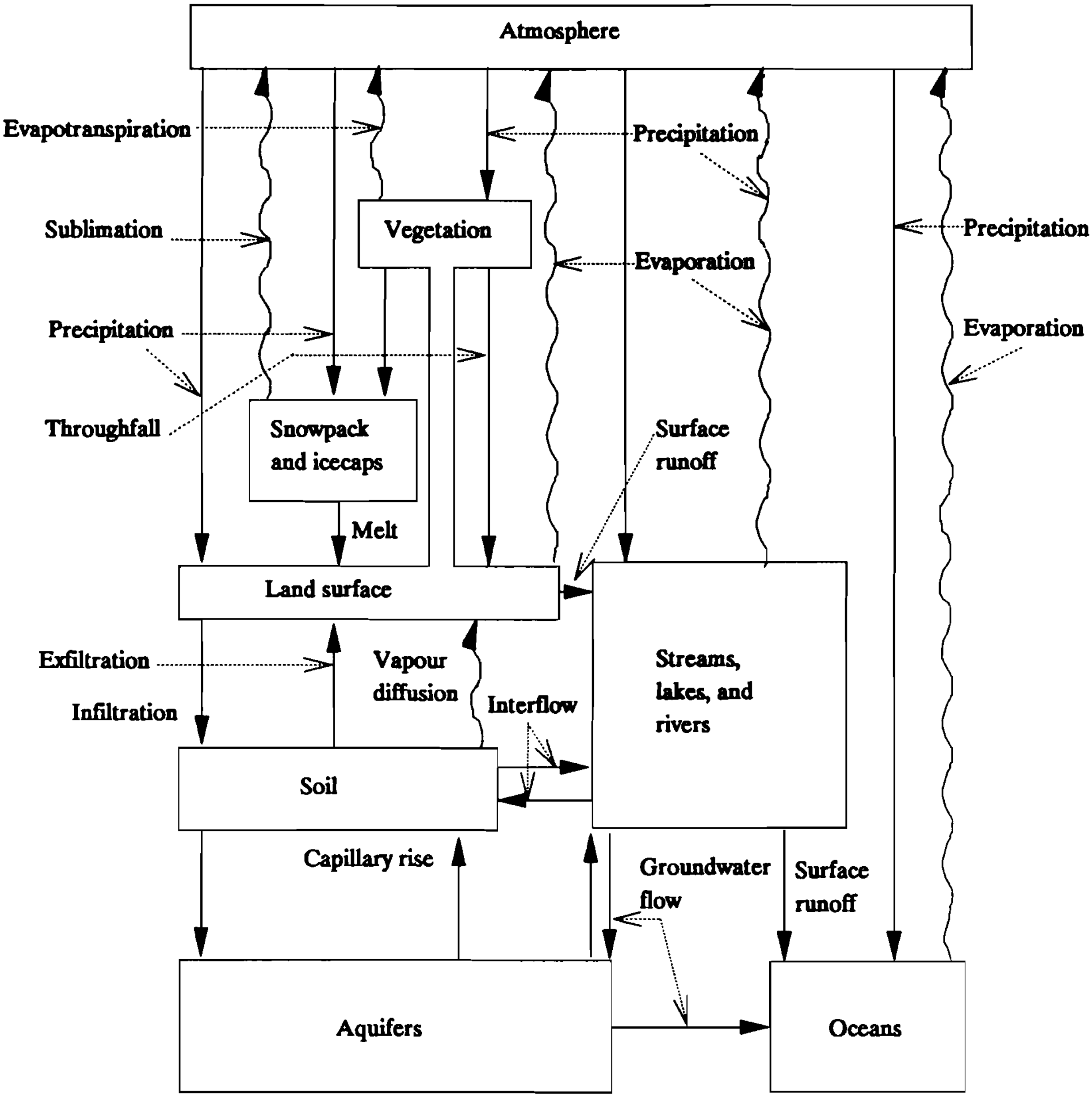


Fig. 5 Hydrological Cycle (after Eagleson, 1970)

resource impacts. For example, a change in seasonal distribution can well override the effects of change in the mean. Moreover, regarding the fact that the climate is measured with the help of moving averages (whether for 10 or 30 years), and considering the natural shorter-term fluctuations of hydrological variables, one can state that detection of a "change" is likely to be diagnosed only well after the fact. This statement can be illustrated by vagaries of the mean global temperature in the period 1910–1975, consisting of dynamic warming in the 1910–1940 period and gradual cooling in the 1940–1960 period. Only after the mid-seventies was a new period of monotonous warming noted. The instance of detection of a climatic change would depend on the form of change (i.e. whether abrupt or gradual). Any delay would have a decisive importance for policy making, and perhaps would render the impact on water studies unusable.

As noted by Askew (1991) "[i]t can ... be frustrating, because there is little likelihood of the climatologists being able to offer predictions of changes in temperature and precipitation with sufficient precision in time and space to make it possible to forecast the resulting changes in soil moisture, streamflow, aquifer levels, flood potentials and the like with any reasonable degree of accuracy." One could perhaps consider the rationale of the work merely as attempts to test the methodology which could later be applied using better input material.

The hydrological studies of climatic change impacts could follow a number of approaches:

- study of long time series of hydrological observations (instrumental) and proxy records; search (with typically negative results) for long-term regularities (periodicities, trends) in these data (e.g. Yevjevich, 1963, 1964, Mitosek, 1992);
- sensitivity studies of hydrological models (what-if philosophy), i.e. introducing changes to characteristics of temperature and precipitation (e.g. Nemec & Schaake, 1982);
- coupling GCMs with hydrological models, treating the output from a GCM as the input to a hydrological model, decomposition of the results of GCMs (few widely spaced nodal points) into individual catchments (e.g. Kaczmarek & Krasuski, 1991, Mimikou & Kouvopoulos, 1991);
- examination of climatic change impacts on hydrological variables which directly and explicitly depend on precipitation and temperature, i.e. standard results from GCMs (McCabe & Wollock, 1992);
- examination of existing hydrological data - search for records similar to a scenario (e.g. if the scenario assumes a certain rise in temperature and precipitation, one examines the material gathered in warmer and wetter years from within the observational record, or looks at the data from another site, with warmer and wetter climate).

Rather than systematically reviewing the hydrological studies, the authors will comment on and illustrate selected aspects only. A review of research on climatic change impact on water resources was recently done by Chang et al. (1992).

The hydrological models have been used to a large extent to find relative sensitivity (analogous to the concept of elasticity in economics) of variables. This notion is useful in the search for amplification effects, i.e. whether small changes in one (climatic) variable may cause substantial changes in another variable, thus aggravating the water problems, in particular in presently vulnerable areas. The sensitivity analysis allows one to judge the impact of the relative increase of temperature (in percent) on the change of hydrological variables of interest (runoff, evapotranspiration). Results of sensitivity analysis are useful in practical what-if considerations.

An early paper by Schaake & Kaczmarek (1979), devoted to climatic change impact on design and operation of water resource systems, examined relations between yield (in % of annual flow) and risk, and relations between temperature, precipitation, and runoff. They advocated a thorough study of transfer functions relating climatic change to water resources. They proposed a framework to study such transfer functions with statistical, analytical, and numerical approaches.

Nemec & Schaake (1982) analyzed the climatic change impacts on catchments ranging from semi-arid to humid, with the help of a hydrological model (US NWS River Forecasting Model, Sacramento). They noted a definite amplification effect between perturbations using precipitation and temperature as the input signals, and flow as the output signal. In a semi-arid catchment a small relative change in the first two variables (10% decrease in precipitation and 1–2°C increase in temperature) would result in a high relative change of the last variable (40–70% drop in runoff). Similar qualitative results were obtained by Kaczmarek (1990), who presented a sensitivity analysis based on closed-form Budyko and Turc formulae. For example, sensitivity analysis of the Turc formula yielded 65 and 84% drops of runoff corresponding to a 10% decrease in precipitation and temperature rises of 1 and 2°C, respectively. Results obtained with the Budyko formula were 41.9 and 45.5%, respectively. The discrepancy between results after Budyko and after Turc means that the values obtained with these methods can be treated as orientation results. In his analysis of a sample drainage basin in the Western U.S., Schaake (1990) showed that if the temperature increases by 2°C, the January-March streamflow would grow by 84.7%, while the July-September runoff would drop by 39.6%. Runoff would seasonally grow following increased winter precipitation, falling as rain rather than snow. Studies on direct impacts of CO_2 increase on vegetation (reduced evapotranspiration) caused several scientists (cf. Aston, 1984) to predict increasing runoff (with no changes in precipitation assumed).

Klemes (1985) analyzed the effect of hypothetical changes in streamflow obtained by Nemec & Schaake, 1982, by examining effects of the climatic change on the reliability of reservoir performance. He demonstrated that, in the case of drier climate, the reliability of "tight" systems (i.e. those, where the draft supply is equal to or greater than two-thirds of the average historical annual flow), could drop drastically and it might be impossible to increase it substantially (for the same level of drought) even with provision of additional storage. There simply may not be enough water in the long term to fulfill the demand and additional, definitely more costly water supply sources would be needed (water transfer; either inter-basin or long distance, deep groundwater, desalination) or additional water saving measures (e.g. pricing, water-saving technologies) to curb water demands would be required. These findings correspond with the ones by Mimikou & Kouvopoulos (1991), who predicted a dramatic increase of risk of annual firm water and requirements of increased reservoir storage to maintain firm yields at tolerable risks.

The main emphasis in Klemes (1985) was placed on the weakness of hydrological models and lack of preparation of the profession for the scientific challenge arising through climatic change considerations. Hydrologic theories were inadequate to address the issues of disaggregation of GCM results. The idea of advanced physically-based models whose parameters depend on temperature and precipitation in a theoretical way is attractive but not realistic. The most rigorous, physically-based models contain empirical, heuristic, conceptual, or even black-box type components. To identify the values of these parameters (or - more difficult - the functional relationships) one has to have an adequate data base. There are several further doubts concerning the level of preparedness of the hydrological profession for climatic change challenges. Consider the extreme hydrological events and flood frequency statistics. There is not much theoretical background supporting the concepts of 1000-year floods, or even 100-year floods, even in the stationary case, if the available time series of observations spans only a few decades. As noted by Klemes (1986) the misleading notions of precision (a flood that on average takes place once in 100 years) should be treated as a public relation expression, which could have been replaced with statements such as "a large flood" or "a very large flood". The objections of Klemes were relevant even in the highly ordered stationary world due to the data scarcity. The confusion grows significantly if the notions of non-stationarity and uncertainties of the climatic change are included.

Several scientists criticized the abuse of mathematical models in hydrology. The word "mathematistry" was used to describe complicated multi-parameter and quasi-physical models claimed to work well by their builders. Such models were undoubtedly "dissertable", i.e. likely to help the builder achieve an academic degree, but they did not improve our insight into processes or our understanding of nature, but rather helped achieve a better fit. Thus the modeling philosophy could be called sophisticated curve fitting.

Klemes (1985) also made several important comments on hydrological modeling. The prerequisite in climatic change impact studies is the verification of climatic transferability, i.e. the likelihood that the model would work well also under changed climate. Transferability and weakness of operational testing are two basic problems. There are more contexts of transferability than that of climate. For example:

- spatial transferability, i.e. the possibility of use of a model tested in location A at another location, B;
- temporal transferability, i.e. possibility of use of a model tested in a time period T_1 in another (in general, remote) time period T_2;
- land-use-change transferability, i.e. the possibility to use a model for a different land use than that for which it has been developed.

The problem may be further complicated by the fact that several of these changes can be combined. Validation of a model at a given scale does not necessarily mean that the model works well at the other levels (i.e. also on levels required in climatic change considerations). The scale problems within hydrology are, despite much scientific effort, still insufficiently understood.

The framework for the use of hydrological models in climatic change related prognostications is structurally deficient. The hydrological models have always been testable. They were backed with observations (typically, in field studies, sometimes even in controllable laboratory conditions). The welcome feedback loop that enables the corrections to be introduced is simply not available in the case of climatic change issues. The observed output signal, with which the result could be compared, is missing. That is, the criticized curve fitting philosophy cannot be followed. There is simply no real observational data to which the curve may be fitted.

One can observe a step backward in sophistication of mathematical models. Instead of complicated, physically-sound, event-based, multi-parametric models, simpler classical approaches are being increasingly revisited. The new climatic change challenge for hydrology brought about the renaissance of simpler models with a low number of parameters, yet with some clear quasi-physical or, at least, conceptual meaning. Orientation common sense results have been obtained with classical engineering type formulae with a few, transparent parameters. The trend of developing models composed of rigorous p.d.e.'s of mathematical physics to describe subprocesses has apparently passed. Such distributed models, with many (possibly, variable and distributed) parameters and many state variables, cannot be identified without an adequate data base. A similar trend is foreseen for water quality models. Rather sophisticated models describing oxygen and nutrient households (see e.g. Orlob, 1982) incorporate around ten state variables and at least five times more parameters. Several temperature functions are used to specify various reactions, but still it would be a mistake to believe that such models can be used to analyze the impact of climatic change. Probably, we should return to classical models such as that of Streeter & Phelps (1926) on the basis we can estimate that e.g. dissolved oxygen deficit in a river will change at least for two reasons, namely due to an alteration in runoff (dilution) and the temperature dependent saturation level. On the other hand, however, we will not be able to speculate on water quality and ecosystem changes more in detail e.g. on how the structure of phytoplankton may change and whether toxic species causing serious drinking water supply problems may not show up (or disappear).

The toolbox of models used contains, among others, classical larger scale, empirical relations. They are typically exemplifications of annual water balance equations, providing links between the components of the hydrological cycle, most notably precipitation, runoff, evapotranspiration, and the change of storage. An additional equation used relates the variables which occur in the mass conservation equation. The simplest example is one of a linear reservoir, where a linear relationship between output and storage is assumed. Many equations used were of empirical origin (correlation or regression-type linkages), some of which are typically regional (i.e. verified on a regional sample of data). The classical and simple models are robust and could give orientation results even in the absence of measurements, in which case, subjective estimates may be used. It is clear, however, that such formulae account for only a portion of a much more complex mechanism.

The existence of GCMs stimulated an interesting evolution of hydrology and new challenges in the development of hydrological models. Interconnections between GCMs and hydrology are of a two-fold nature. On the one hand, hydrological models are needed for spatial and temporal disaggregation of GCMs. In other words, they are needed to translate the GCM projections of climatic variables, available in widely spaced grid nodes into more local information of hydrological relevance. Hydrological models should account for heterogeneities at the subgrid scale – topography, soil, land use, vegetation, albedo, orography, water bodies, wind direction, etc. On the other hand, suggestions have been made of better ways of representation of hydrological processes that could be used within the GCMs. It is the problem of parameterization, i.e. representation of subgrid-scale phenomena. The need for parameterization comes about if the processes are too complex, too small, too fast, or too heterogeneous to be directly and explicitly represented in a GCM. The practical ways in which the parameterization could be achieved range from neglect of the process in question, through using empirical, semi-empirical, or theoretically justified approaches.

The land surface hydrology module in a GCM should divide the precipitation into runoff and infiltration (i.e. losses, in the traditional effective rainfall approach). The early approaches were rather primitive. The Budyko bucket representation assumed that the runoff was only produced by the exceedance of soil capacity. In another classical approach the runoff was assumed to be a fraction of precipitation, and the actual evapotranspiration a fraction of the potential evapotranspiration. The partitioning coefficients were controlled by the soil moisture.

Several improvements in representation of land surface processes within GCMs have taken place in recent years. Two better known approaches are the SiB (Simple Biosphere, cf. Sellers et al., 1986) and BATS (Biosphere-Atmosphere Transfer Scheme, cf. Dickinson et al., 1986) schemes. These improved representations incorporate greater detail of the soil-vegetation-atmosphere transfer of heat, momentum, and moisture.

Entekhabi & Eagleson (1989) suggested a further way to improve subgrid scale parameterization in a GCM by better representation of the land surface hydrology. The idea resulted from the observation that uniform distribution of rain over the entire grid surface did not agree with strong spatial variability observed in the nature. Uniform distribution of rainfall means that precipitation intensity is assumed to be low everywhere. This causes a serious overestimation of evapotranspiration and a significant underestimation of runoff. Entekhabi & Eagleson (1989) introduced the spatial probability distribution of rainfall and soil moisture within the grid surface. The distributions used to represent the above two variables were exponential and gamma, respectively. The exponential spatial probability distribution of rainfall assumes that there exists a small area of very high precipitation intensity, as opposed to a big area with low rainfall. Johnson et al. (1991) noted that the frequency of precipitation is also poorly reproduced by GCMs. Thus the frequency of time periods with precipitation is another measure of potential usefulness in testing of models. However, the prospects for parameterization-induced improvements are not unlimited. Even if global estimates are right, significant errors in regional precipitation occur. As noted by Johnson et al. (1991), "errors in precipitation create errors in the water balance which are impossible to correct with any landsurface parameterization".

Independent of the need for spatial disaggregation of prognostications given in remote nodes of the GCM grid, a sort of temporal disaggregation is also required. Monthly data received from GCM experiments are not meaningful for a variety of hydrological processes. It is the temporal resolution of processes that does matter in several event-driven cases. A single storm of high intensity may be responsible for a catastrophic flood, overland flow, and the bulk of erosion, a large portion of the annual nitrogen and phosphorus transport, or a significant fish kill. It is well known from the rainfall-runoff theory that such details as storm temporal resolution and direction of storm movement strongly influence the outflow (similar statements could be formulated for lake water quality problems). It is not mean precipitation that counts in a variety of applications, but rather the characteristics of extreme events.

Kundzewicz et al. (1993) analyzed the performance of water resources systems in the load-resistance and excursion theory frameworks. They considered the time series of water resource analogues to the concepts of load and resistance (most obvious analogues: water demand and water supply). Nonstationary behavior of the system means that the frequency (also duration, intensity) of the nonsatisfactory system behavior, i.e. of load exceeding resistance (water demand exceeding water supply) will change. Predictions indicate that in many areas of the Globe water resources systems will be increasingly under stress, which can be visualized by nonstationary load and resistance series (growing load, decreasing resistance, Fig. 6a). This can be also presented as densities of load and resistance (Fig. 6b). It is plausible to assume that the overlapping areas of the densities of load and resistance would grow with time.

6 Are we Sufficiently Preparing for the Global Changes Likely to Occur?

The above caption was a title of an important, well organized and well attended session at the international conference. Two expressions contained in the title of the session usually raise the requirements of precision (Kundzewicz, 1991). Are we capable of achieving precision, as far as the wording "sufficiently" and "likely" are concerned? Hearing "sufficiently" one may ask – for what? Isn't the very notion of sufficiency subjective? Where is the boundary between "sufficient" and "insufficient"? Doesn't it depend on the risk attitude of an individual, a group, or a society? Systems may perform well judged by one set of criteria, important in a given statement of the problem, while their performance may be rated as poor if another set of criteria is accepted. The word "likely" suggests that we could quantitatively answer the question – how likely? Unfortunately, this is not the case. No experts dare to assess the likelihood of scenarios, not to mention assessing the even more obscure likelihood of consequences. Therefore (Kundzewicz, 1991), it does not seem possible to achieve a desired precision in elaborating on these terms. They are qualitative expressions which have a public relations flavor.

It should be stressed that the term "global change" embraces much more than the climate. There is a real exogenous global variability. Population growth, development aspirations of nations and individuals, attempt to reach higher standards of living, and changes of land use have already been observed.

However, it is likely that locally public opinion can be increasingly confident in climatic change. It is the common feeling of a broad public in Central Europe that there has been much less snow and frost in recent times and that summers are hotter than before. The phenomena of drought and wildfire have never been experienced to the present extent.

It is unanimously agreed by all of the interested parties that one should strive towards reducing uncertainties in understanding and assessment of climatic change and its consequences. IPCC (1990) identified the key areas of scientific uncertainty responsible for the non-satisfactory credibility of simulation and predictions. These areas relate to clouds, oceans, greenhouse gases and polar ice sheets (IPCC, 1990). There have been several international research activities already undertaken towards reduction of the above key areas of scientific uncertainty. Advanced research and accurate world-wide observations (both remotely-sensed and in situ, surface-based) are likely to lead to more credible predictions of climatic change.

However, even if there is a consensus on the need for further research into climatic change issues with the view of "narrowing uncertainties", there exists an obvious trade-off connected with choice under constraints (finite budget). Spending more on climate research (world expenditures

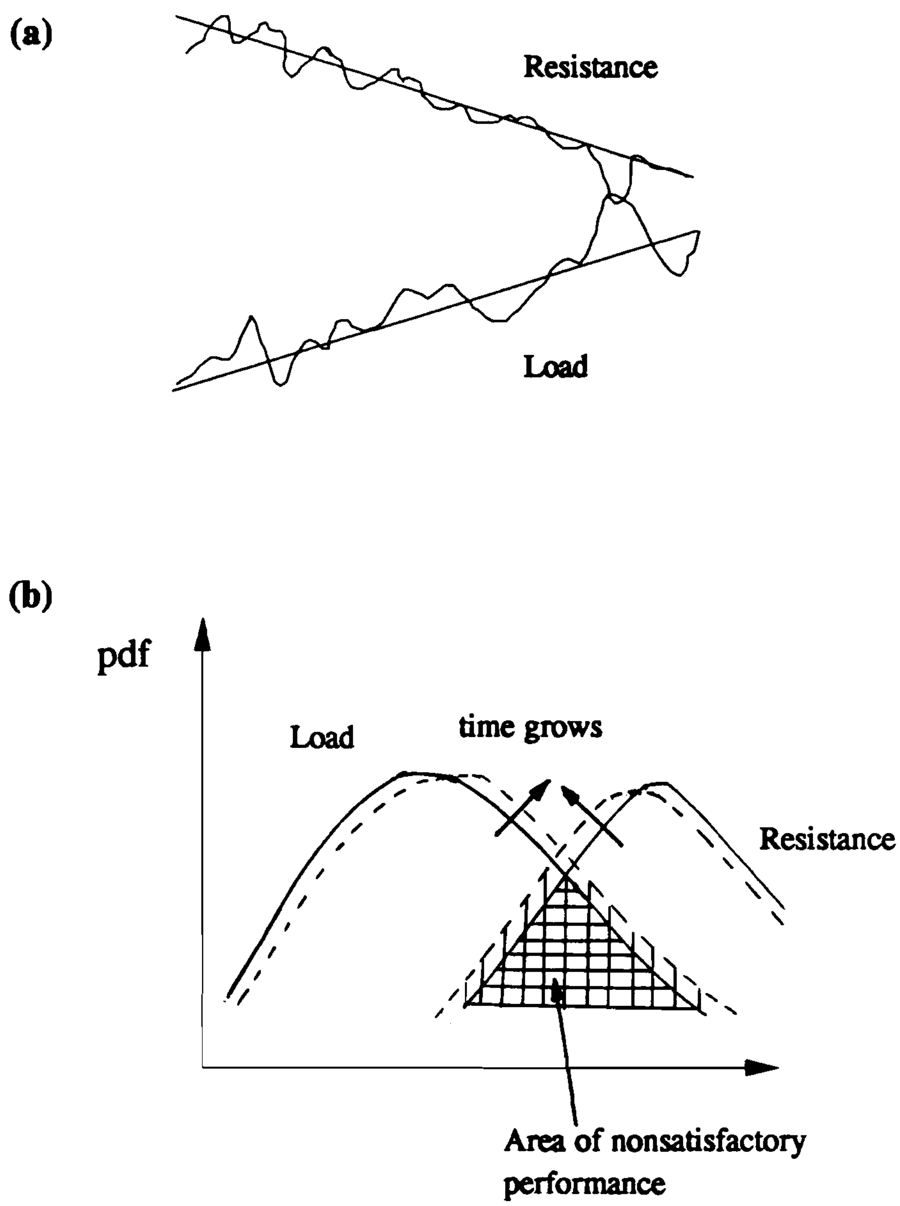


Fig. 6 Increasing stress on water resources in the load-resistance framework (load-water demand, resistance-water supply)

reach one thousand million dollars) means reduction of funds for other research areas. Reading the calls for "narrowing uncertainties" one has the impression that we know how big they are. Perhaps they are of the order of the variations predicted, perhaps smaller, or perhaps greater. What it should mean, rather, is narrowing the uncertainty band, without a sound orientation of how "narrow" the uncertainties are before and will be after the process of narrowing.

Moreover, it cannot be excluded that more research may increase the uncertainty. As noted by Klemes (1991), "while on the one hand, it may provide us with more specifics, thus reducing the current level of the related uncertainties, on the other hand it may reveal a greater amount of uncertainty in the system than the current consensus, thus lowering the predictability for below the present expectations".

Climatic change issues need concerted international actions. Many important international endeavors have been already undertaken. The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) jointly sponsored the World Climate Research Programme (WCRP), whose aim was to promote related scientific research and to develop prediction capabilities. Among the components of WCRP are large-scale experimental and numerical programs aiming at the development of improved models of the climate of the Earth. The Global Energy and Water Cycle Experiment (GEWEX) together with the Tropical Ocean and the Global Atmosphere (TOGA) and the World Ocean Circulation Experiment (WOCE) aim to reduce uncertainties in present assessments.

A high-ranking international endeavor is the Intergovernmental Panel on Climatic Change (IPCC) established by the World Meteorological Organization (WMO) and by the United Nations Environmental Programme (UNEP). It deals with science, impacts, and policy, and developing countries. The report of IPCC (1990) and the update of 1992 prepared by several hundred scientists are perhaps the most authoritative statements on climatic change ever made. It is a standard reference work for today.

Another important endeavor is the International Geosphere-Biosphere Programme (IGBP) of the International Council of Scientific Unions (ICSU). It is a world-wide interdisciplinary research initiative to enhance understanding and modeling (description) of interactive physical, chemical, and biological processes that control the system of the Earth. IGBP would provide the biogeochemical components necessary in the analysis of the climatic change and its broad impacts. There is a strong component of direct interest to hydrological sciences – studying Biospheric Aspects of the Hydrological Cycle (BAHC).

IPCC analyzed the adaptive responses to global climatic change. They devised a menu to help societies adapt to climatic change by anticipation and reduction of negative impacts, while capitalizing on positive aspects.

Responses should comprise prevention, limitation, compensation and adaptation, in all senses (technical, economical, legal, social, political). Definitely, limitations pertain also to areas beyond the water sector (slowing down the emission of greenhouse gases, efficiency of use of energy, water, and raw material, fuel switching, reforestation, pricing).

General IPCC recommendations and criteria of response actions stress the importance of:

- Flexibility (keeping options open, e.g. via market mechanism for pricing and allocating resources);

- Economical justification. That means "doing things that make sense anyway", i.e. decisions that would be justifiable also in the absence of climatic change (e.g. – it's always good to save energy, water, raw materials);

- Timing. Expensive adaptation actions should not be realized unless the expected cost of inaction is very high. Necessary steps include determination of a critical point in time, before which the adaptation strategy needs to be implemented, and determining how much time it takes to efficiently develop the response;

- Feasibility. Understood as the consistency with arrangements of a legal, institutional, political, social, cultural, and financial nature. It may be necessary to modify any of the above.

There are a number of questions pertaining to parameters of diagnosis and actions being frequently asked. The diagnosis component embraces such questions as: What can happen? When? How fast? At what sequence? Finally, there is a natural question on credibility of the answers to the above problems. The action component raises similar questions: What to do? When to start action? How fast to proceed? How to incorporate the updating mechanism? What are the costs of action, as compared to the cost of no action?

A typical assumption at international high-level meetings has been that we are able to detect problems in advance. It is assumed that we do not need to wait until catastrophes occur and only then search for remedies. However, as experience shows, it is indeed an occurrence of disaster (flood, drought, wildfire) which triggers allocation of money for research and for actions. There have been ample illustrations of the latter statement.

The political systems typically do not take up unknown problems. In order to deserve room in the political agenda (i.e. the status of a major national issue in the US) the problem should be (Ingram et al., 1990) solvable, serious, certain, likely to happen soon. Moreover, there should be a sinner to be blamed. Under these circumstances, it does not look like the climatic change issue can be considered worthy of concerted attention of policy makers. However, there are some contradictory declarations. In her speech delivered at the Conference on Climate and Water (Helsinki, Finland, 5 September 1989) convened by the World Meteorological Organization (WMO), Mrs. Birgitta Dahl, Swedish Minister of Environment and Energy stated (World Meteorological Organization, 1989):

"Information given by the scientific community concerning the scale of climate change and its consequences is not totally concordant. We are all aware of the fact that in the society of research there are – and should be – doubts about the absolute truth. But we as politicians cannot await the final results. Incomplete results are often used as an excuse not to take necessary measures ...

Of course we need more research, but the decisions needed cannot await the final results. We have to take brave and responsible action now – and to be prepared to sharpen our tools when new knowledge and technology is made available".

One can say, following S. Schneider, that the crucial question is: "whether we can afford to be unprepared for the possibility of disaster and not – whether we can prove conclusively that disaster really lies ahead".

Climatic change prognostications brought much confusion to planning and design authorities. There is a dilemma as to how to proceed. Is it rational to ignore the climatic change signal, simply on the basis of high uncertainty involved? Or, perhaps, the warnings should be taken seriously and bigger storage volumes requested to cope with sharpening extremes. That is, larger reservoirs are to be designed and built, to accommodate larger flood waves due to increased winter rainfall and to better fulfill the growing demand for water during the prolonged droughts of increasing severity during the vegetation season. However, even in the areas where several GCMs are in qualitative agreement that there will be more water in winter and less water in summer, there are no reactions in practice from the side of decision makers. It would be embarrassing indeed, if the predicted changes in runoff do not occur. Whom to blame for overdesign? What design value to take if the scientific authorities give, at best, a broad range of values? How to translate the spectrum of possibilities into one definite value needed for design of a dam or a spillway?

It should be noted, however, that climatic change uncertainties are not the only uncertainties related to design problems. Long-term prediction of water needs is far less certain than the uncertain assessments of future water supply.

Klemes (1992) stressed that the only message concerning policy making that can be considered as scientifically supported can be summarized as "Beware, the climate may get worse, possibly within a couple of decades or so (should it get better, policy makers need not worry ...)". "Worse" may mean (Klemes, 1992):

- less water available;
- greater extremes and fluctuations in general;
- less advantageous seasonal distribution of precipitation and/or runoff.

There is a broad consensus that presently it is not possible to quantify any of these three changes for any specific location, either their extent, time or rate of occurrence, or even their direction. The only feasible way of taking them into account is treating them as an increase of uncertainty in water-related decision making.

Ample exemplifications of this sort of dilemma can be found in the literature. McCabe & Wollock (1992) studied climatic change and climatic variability impacts on the moisture index in the basin of the river Delaware. They used estimates of changes in mean annual precipitation resulting from three GCMs. One GCM predicted a drop in precipitation of 46 mm, whereas another GCM predicted a rise in precipitation of 143.9 mm. Indeed, the situation resembles the rhetoric of Klemes (1991), who used the wording: [it] "is just a convoluted and pretentious way of saying 'I don't know.' This is not information, it is information pollution". However, this sort of information is all that hydrologists can use as the input material of their studies. Based on two GCMs McCabe & Wollock (1992) predicted a significant decrease in the moisture index, whereas, utilizing the third GCM, they did not predict a significant change.

Urban water supply specialists (Schwarz & Dillard, 1990) presenting the situation in the U.S. stated that "various components of urban systems are resilient and could accept early manifestation of climatic changes without undue damages. Most urban systems would be able to cope with the change. Coping would, however, be costly." There are definitely more examples of this kind, where risk-averse societies are willing to pay for a significant safety factor in order to avoid failures. Such overbuilt systems could work well also under new, more difficult (e.g. climatic change) conditions. This situation, however, does not hold universally. It is sufficient to refer to tremendous problems of megacities or to those stemming from aged infrastructures or the risky operation of vulnerable facilities such as large, sophisticated wastewater treatment plants. In fact, some of the basic principles of traditional design of urban water resources systems are currently in question (see e.g. Niemczynowicz, 1991); climate change would just add an additional dilemma.

Important water-related response strategies were compiled by IPCC (1990). Three basic categories of responses were identified there:

A augmenting our data base to make reasonable judgments (inventorying, monitoring, assessment, and transfer of information and technology);

B responses that are economically justified under the present-day conditions (e.g. improving efficiency of use of the harvested resource);

C longer term and more costly measures. They are applicable once uncertainties are reduced (preparing communities, e.g. for a shift in agriculture, building a new dam, etc.).

It is recommended to follow the responses rated as (A) and (B) right now and in the foreseeable future. Category (B) envisages actions aimed at solving the problem if it exists, yet that are advantageous even if the problem does not exist.

Some of the recommendations of IPCC (1990) follow; the capital letters used in brackets refer to the above categories:

A: enhancement of measurement, monitoring, scientific knowledge, and forecasting; education and technology transfer; financial assistance with special consideration of developing countries; improvement of flood forecasting;

A,B: determining flexibility and vulnerability of current water supply systems; system optimization; water conservation;

B: demand management through water pricing; voluntary water transfers or markets; evacuation plans, flood warning; floodplain zoning; flood insurance;

B,C: water-saving tillage systems: dam safety and other design criteria; adjustments in protecting water quality in rivers and reservoirs; utilization of hydropower; disaster relief and emergency preparedness; water structures design modifications;

C: modification of cropping systems towards water conservancy; adjustments in protecting estuarine water quality; adjustment in river transportation; modification of water storage and other water augmentation measures;

It should be noted, however, that in several instances the feasibility of response strategies is questionable. There is, for instance, a strong opposition to water power development schemes in several countries of the world.

Anticipatory policies would be necessary if the project life time is long enough to deal with possibly changed climate. Water storage reservoirs undoubtedly belong to this category. On the one hand, a dam should not be constructed now in anticipation of being needed in several decades. On the other hand, if a dam is being built now, it may be useful to "design-in" the possibility of further augmentation. This is again a call for flexible design, with possible variants, depending on the development of situation.

It seems interesting to note the recommendation devised by Fiering & Rogers (1989) to agencies responsible for water engineering designs (reservoirs, spillways). In their opinion there was a need for "a policy statement each year or two from the Chief ..., declaring that planning ... during the coming period will be based on the assertion that the climate is, or is not, changing". Such a policy statement, subject to periodical updating, would imply whether or not the conventional stationarity assumption is a rational one for the time span of the economic life of the system.

The authors share the spirit of Klemes (1991) that "the issue of climate change has been blown out of all proportion, both as to the actual degree of its current understanding and as to its potential impacts on the planning and design of water resources projects ... [It] ... seems to be a convenient excuse for current runaway expansion of consulting business in simplistic mathematical modeling, and, on the political scene, a convenient smoke screen behind which more important and urgent issues can be hidden ..."

Klemes (1991) formulated a short list of commonsense recommendations. He urged the human race "to pause and reexamine its modus operandi" and to undertake such measures as:

"1. Containing the primary sources of danger that are already in operation.

2. Neutralizing the causes that have led to the present situation.

3. Learning more about the functioning of the global level system so as to see its weak and fragile elements more clearly."

7 Promising Research Areas and the Role of IIASA

The analysis offered thus far aimed to demonstrate the weaknesses of the present state of the art of research into climatic change and its consequences. The uncertainties are very strong and pertain to the lack of knowledge and understanding of the processes in their complex and interconnected form. Two conclusions could be drawn from such a diagnosis; either science has no chance to arrive at any results of importance in reasonable time, due to the immense lack of knowledge, data, understanding, etc; or science has a great challenge to evaluate the situation, and improve quantitative assessments, which would be of value in practice. The first option means no more research in the field. It is a waste of money and effort. Wait for more evidence and collect a sound data base. The other option means more research (though more precisely targeted) is needed into the area. The authors support the second option.

The international scientific community has recognized the need for a concerted action on the worldwide scale aimed at reducing uncertainties in modeling climatic changes and their impacts. This embraces improving GCMs via better subgrid parameterizations and devising better tools to translate GCM results to the spatial and temporal scale of hydrological and water resources concern. Worldwide extension of the observational data base is also needed. This gave rise to a number of large scale international projects which have already been undertaken or are being planned. This field of activities, although undoubtedly most substantial for improving our understanding, is apparently apart from the areas of scientific expertise of IIASA.

The authors second the IPCC (1990) recommendations that there is a definite need for an international inventory of water-related large scale (regional, continental, global) vulnerabilities. Such an inventory could embrace both the existing vulnerabilities (and in particular those that are likely to aggravate) and future foreseeable vulnerabilities that may occur even in the areas that are currently flourishing and problem-free. A national U.S. inventory of vulnerabilities of water systems has been developed by Gleick (1990). This sort of approach seems badly needed at a much broader, international scale. World inventory of regional vulnerabilities pertaining not only to the climatic change but also to other possible changes (population, agriculture policy) was studied by Kulshreshtha (1993). A more detailed analysis with a strong focus on the role of uncertainties of regional scope is a challenging avenue.

The authors believe that the systems approach in general and IIASA in particular could play an important role in the international and multi-disciplinary scientific endeavors towards analysis of climatic change impacts on water resources, by offering the capabilities and methodologies of systematizing scarce and largely uncertain information.

There have been several IIASA contributions in the past related to climatic change impacts on water resources. Kaczmarek (1990) presented a theoretical discussion of a sensitivity analysis of river runoff to changes in precipitation, air temperature and net radiation. He discussed the rationale questioning the results of sensitivity analysis established in the literature. Kaczmarek & Krasuski (1991) developed and tested at IIASA a meso-scale hydrological model based on the stochastic storage theory. They performed sensitivity analysis and water balance impact studies. Salewicz (1992) analyzed the operation of the hydropower scheme on the river Zambezi both under current climate and for a scenario for future climatic conditions. Szilágyi & Somlyódy (1991) analyzed the impact of climate change on inorganic carbon household of lakes. Somlyódy and his coworkers performed a systematic, global analysis of likely changes in the ice cover and stratification pattern of lakes (Mayer et al., 1993). The climatic change problems in reference to water quality aspects in lakes and reservoirs were discussed in a comprehensive fashion by Varis & Somlyódy (1993). There have been several collaborative efforts at IIASA related to climatic change impacts on water resources, some of which were reported in the series of IIASA collaborative papers. Falkenmark (1989) presented disturbances of water-related phenomena caused not only by climatic change, but also by other global changes. Ryszkowski et al. (1989) dealt with hydroecological consequences of climatic change in Poland. They sketched the possible impact on water balance scheme. Ozga-Zielińska et al. (1991) worked out a meso-scale hydrological model for the river Vistula, translating GCM results into hydrological variables. Mitosek (1992) analyzed longtime series of hydrological data and indices, checking the hypothesis of stationarity and ergodicity of the parameters. He showed that, at the accepted significance level (5%), the analysis based on two non-parametric tests cannot reject the stationarity and ergodicity hypothesis in a large majority of cases considered.

While leading the water project at IIASA in 1989–1991, Kaczmarek undertook an international activity towards preparing a monograph (1992), whose first part would contain the worldwide information on regional models. The monograph will contain contributions of eminent scientists gathered around the idea of IIASA and Kaczmarek's concepts.

It is the opinion of the authors that the studies of climatic change impacts on water resources will remain a challenging research area in the near future. There are several components on which the IIASA activity could focus. They will be elaborated in the sequel.

1. It seems worthwhile to continue the efforts of IIASA commenced by Kaczmarek, aimed at studying water resources under changing climate. There is a need to start collecting the necessary data on climate, hydrology, economy, and population for a region, or an individual drainage basin of a case study. The data should pertain both to the present day situation and to projections into the future. The future climate and hydrology could be derived via meso-scale hydrological modeling from the available outputs of the GCMs.

   The case of Central Europe, described in the research proposal of Kaczmarek (1992) lends itself well as an interesting case study area for mapping water related stress. The water problems in certain parts of this region are serious already under the present climate, and the water related stress may drastically aggravate as a result of even a slight adverse climatic change. This might lead to a spectrum of perturbations in a number of economical, political, and social contexts. As proposed by Kaczmarek (1992), extensive studies can be carried out related to regional water balance, energy balance, and temperature of inland water bodies. The second phase of this study foresees an analysis of case studies for assessing climatic change impacts on water resources and the policy implications.

   The concept of this study is well documented and advanced enough for initiation of the research. The idea of creation of the solid data base foreseen in this study can be complimented. Moreover, once established, the data base can serve different purposes, being a factographic foundation of various possible projects, which could be undertaken at IIASA in the future.

2. A recommendable component of the IIASA research in the area of climatic change impacts on water resources could follow the extension of the classical hydrological perspective, following the approach devised by Bárdossy & Plate (1992). The classical hydrological scale of concern is one of a catchment and the perspective was typically related to rainfall-runoff modeling, i.e. transformation of effective rainfall into surface runoff (Fig. 7). The point of departure of Bárdossy & Plate (1992) was the observation that GCMs reproduce air pressure spatial fields fairly well, while failing to accurately reconstruct the precipitation. Bárdossy & Plate (1992) devised a scheme starting from the air pressure map, via pattern recognition module, determining the synoptic scale circulation (Großwetterlage) to probabilistic assessment of rainfall related to particular circulation types. This philosophy extends the hydrological perspective, i.e. treats the precipitation not as an input, but rather as a result; an output from a pre-hydrological model. The above concept is useful in weather generator applications. When studying scenarios and propagation of changes, one could use GCM air pressure maps and the methodology devised by Bárdossy & Plate (1992) in order to arrive at characteristics of the precipitation process. It seems to offer better quality characterization of rainfall than could be obtained directly from GCMs and it could be applied to one or more case studies.

3. A further component of the activities could be called a water management vulnerability study with a strong focus on uncertainties for the watershed chosen as the case study site. It would require a concerted action of a multi-disciplinary group at IIASA, composed of hydrologists, water resources specialists, and decision and system scientists. A need for such an endeavor is strongly felt by the authors. Three elements of this well suited research component are identified, which could be undertaken complementarily or selectively. They will be elaborated in the sequel.

3a. GCM outputs are highly imperfect, may substantially vary from model to model and there seems to be no hint as to which GCM to choose (Fiering & Rogers, 1990 - "which model you choose to believe"). Therefore, instead of treating the GCM-derived information as the direct input to future studies, an alternative methodology is needed which avoids the bias of the direct use of a single GCM.

A systematical procedure that comes to mind is using judgments of an interdisciplinary group of experts who know the results of GCM modeling, historical time series of variables and other relevant information. This area undoubtedly belongs to the realm of systems analysis; that is, to the scientific mandate of IIASA. The situation resembles the one sketched by Miser & Quade (1988), calling for application of systems analysis. "In the absence of hard data, expert opinion can have an important role in supplying 'soft' judgmental inputs". The areas, where the expert judgment may play an essential role, that is, "designing the structure of models, including modifying existing but inadequate models; supplying judgmental input data, especially in the form of forecasts; ... and offering normative visions of the future and inventing strategies for their attainment" (Helmer, 1988), are very relevant in the present context. There are a plethora of methods, which lend themselves well to the application (e.g. interactive simulation, gaming techniques). The use of the Delphi technique, i.e. an integrative device for blending subjective, qualitative judgments issued by several experts (GCM specialists?, hydrologists?, water managers?) comes immediately to mind.

However, even if the experts arrive at the consensus of opinion, it is still opinion. It does not necessarily mean that the experts are right. As pointed out by Klemes (1993, personal communication), there have been several cases in the past when the consensus of expert opinions was highly misleading. As an example, consider the concept of ether accepted universally at the end of the last century. Similarly, the consistent "expert opinion" about the timing of the disappearance of the U.S.S.R. gathered only five years ago would have nothing in common with the real development of events.

3b. There is no established methodology to update the pool of information available. Repeated issuance of an updated statement, where old and new information are blended, would aid the decision makers to improve their assessments, predictions and decisions in the light of the new evidence arriving. Some type of feedback structure is needed in order to incorporate the progress of understanding, better adequacy of models (e.g. improved GCMs, as far as scale, parameterization, and verification are concerned), improved accuracy, and coverage of observations and growing time series, that ultimately could prove more clearly that the climate is or is not subject to change. Extension of the observation record available seems to be the most serious candidate for providing evidence of climatic change. One of the possible updating procedures would be based on the Bayesian methodology. It would start from the evaluation of the subjective probability density of some alternative, hypothesis, or parameter (following experts' opinion, literature search, results of modeling, previous experiences and last but not least common thinking). The prior density may be very poor and flat, and thus of low information content. However, once new evidence arrives, it should be used to update the diffuse density via the likelihood function and then to arrive at a better posterior density, likely to be tightened by the new information. Although, as stated by Fiering & Matalas (1990), "for the foreseeable future the evidence probably will not - indeed, cannot - be strong enough to overwhelm a noninformative prior ... But ... policy, plans and designs must be drawn before there is enough accumulated evidence to support or reject a position on climate change." That is, the decisions must be made in the uncomfortable position of flat, uninformative densities. Rational organization of the scarce existing information, on account of substantial gaps of knowledge, does definitely belong to the mandate of IIASA.

3c. Scholars of IIASA have played a significant role in suggesting criteria aimed at versatile description of unsatisfactory performance of systems. The concept of resiliency, authored by

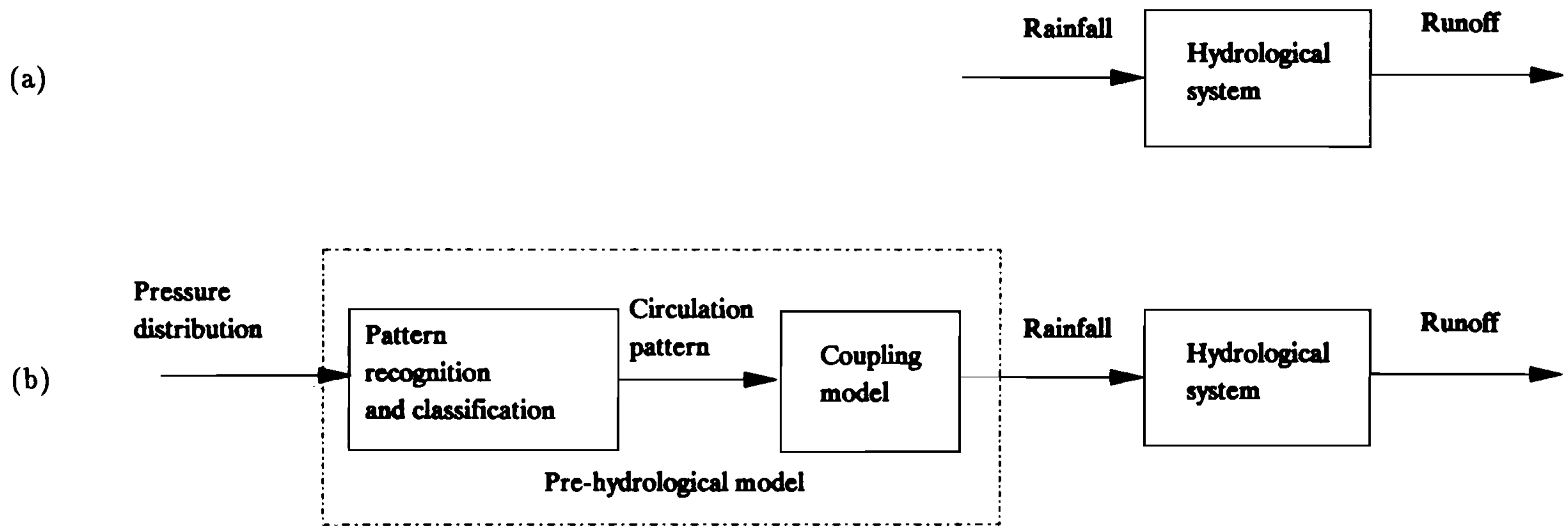


Fig. 7 Extension of the hydrological perspective
(a) Traditional approach
(b) Approach suggested by Bárdossy and Plate (1992)

Holling (1978), was reflected in a number of his papers while at IIASA. The set of papers of other scholars connected to IIASA (Loucks, Hashimoto) published in Water Resources Research in 1982 raised considerable interest worldwide. However, it is the feeling of the authors that the above criteria have not been satisfactorily translated into actions and design guidelines or standards in the water sector, even before the advent of climatic change issues. Nevertheless, at least verbally, the ideas of reliability, resilience, vulnerability and robustness, elaborated in the references above, have penetrated the climatic change literature allowing the decision makers to conceive reliable, resilient, and robust solutions, and to reduce the vulnerabilities. These and related notions of safety, flexibility, adaptation capacity, possibility to accommodate a surprise, safe-fail, as opposed to fail-safe design, etc. sound good and appeal to common sense, but are rather vague when it comes to practical implementations. No methods of developing robust design or operational strategies have been elaborated. A definite need exists to translate these criteria into rules of hydrological and water resources design. The present element of this research component will be strongly focused on the case study selected, with thorough consideration of water supply, water demand, and water management problems. A novel statement of the design problem is needed, leading to structurally robust systems of solutions. Recommendation of a prudent stepwise design policy could alleviate the problem of accommodation of uncertainties (surprises). Follow-up to the research pioneered by IIASA on reliability related notions in the new framework of climatic change impact on water resources seems a challenging task.

All three research components analyzed above are complementary and subtly interwoven. Therefore, most preferably, they should be conducted jointly.

4. Last but not least, the fourth obvious field of research for IIASA would be to continue the studies on climate change and water quality. This is a highly unexplored area where lots of avenues can be followed. For instance, quality context can be added to any vulnerability studies mentioned before. The continuation of lake analysis towards nutrients and eutrophication would be another logical choice. Also, research on specific lakes would be welcome to justify conclusions of the "global" thermal stratification sensitivity study. Finally, the application of concepts outlined under item (3) and in Varis & Somlyódy (1993) also forms a field promising valuable future results.

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9 References

Askew, A.J., 1991, Climate and water - a call for international action, Hydrol. Sci. J., 36(4), 391–404.

Aston, A.R., 1984, The effect of doubling atmospheric carbon dioxide on streamflow: A simulation, J. Hydrol., 67, 273–280.

Bárdossy, A. & Plate, E.J., 1992, Space-time model for daily rainfall using atmospheric circulation pattern, Water Resour. Res., 28(5) 1247–1259.

Chang, L.H., Hunsaker, C.T. & Draves, J.D., 1992, Recent research on effects of climate change on water resources, Water Resour. Bull., 28(2) 273-286.

Dickinson, R.E., Henderson-Sellers, A., Kennedy, P.J. & Wilson, M.F. (1986) Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate model, NCAR Technical Note TN-275+STR, 69 pp.

Dooge, J.C.I., 1986, Climate change and water resources, Lecture presented at 38th session of the WMO Executive Council, WMO No. 675.

Entekhabi, D. & Eagleson, P.S., 1989, Landsurface hydrology parameterization for atmospheric general circulation models including subgrid scale spatial variability, J. of Climate, 2(8), 816–83.

Falkenmark, M., 1989, Global-change-induced disturbances of water-related phenomena - the European perspective, IIASA, Collaborative Paper, CP-89-001, 41 pp.

Fiering, M.B., 1982, Alternative indices of resilience, Water Resour. Res., 18, 33–39.

Fiering, M.B. & Matalas, N.C., 1990, Decision-making under uncertainty. In: Waggoner, P.E. (Ed.), op. cit.

Fiering, M.B. & Rogers, P., 1989, Climate change and water resources planning under uncertainty, Report for U.S. Army Institute for Water Resources, Fort Belvoir, VA.

Gates, W.L., 1985, Problems and prospects in climate modeling. In: Radok, U. (Ed.), Problems and Prospects in Climate Analysis and Forecasting, Westview Press, Boulder, Colorado.

Giorgi, F. & Mearns, L.O., 1991, Approaches to the simulation of regional climate change: A review, Reviews of Geophysics, 29(2) 191–216.

Gleick, P.H., 1990, Vulnerability of water systems. In: Waggoner, P.E. (Ed.), op. cit.

Hashimoto, T., Stedinger, J.R. & Loucks, D.P., 1982, Reliability, resiliency and vulnerability criteria for water resource system performance evaluation, Water Resour. Res., 18, 14–20.

Hashimoto, T., Loucks, D.P. & Stedinger, J.R., 1982, Robustness of water resource systems, Water Resour. Res., 18.

Helmer, O., 1988, Using expert judgment. In: Miser, H.J. & Quade, E.S. (Eds.), 1988, Handbook of Systems Analysis. Craft Issues and Procedural Choices, Wiley.

Holling, C.S., (Ed.), 1978, Adaptive Environmental Assessment and Management, Wiley, Chichester.

Hulme, M., Wigley, T.M.L. & Jones, P.D., 1990, Limitations of regional climate scenarios for impact analysis. In: Boer, M.M. & de Groot, R.S. (Eds.), Landscape-ecological Impact of Climatic Change, IOS Press, 429 pp.

Ingram, H.M., Cortner, H.J. & Landy, M.K., 1990, The political agenda. In: Waggoner, P.E. (Ed.), op. cit.

Intergovernmental Panel on Climate Change (IPCC), 1990, Climate Change. The IPCC Scientific Assessment, Cambridge University Press.

Jaeger, J., 1988, Developing policies for responding to climatic change. A summary of the discussion and recommendations of the workshops held in Villach, 28 September to 2 October 1987, WCIP-1, WMO/TD No. 225.

Johnson, K.D., Entekhabi, D. & Eagleson, P.S., 1991, The implementation and validation of improved landsurface hydrology in an atmospheric general circulation model, Report No. 334 (R91-23), Ralph M. Parsons Laboratory, Hydrology and Water Resource Systems, Massachusetts Institute of Technology, Cambridge, Mass., U.S.

Kaczmarek, Z., 1990, On the sensitivity of runoff to climate change, IIASA, Working Paper, WP-90-58.

Kaczmarek, Z., 1992, Water resources under climatic stress: the case of Central Europe, Collaborative Research Proposal (unpublished).

Kaczmarek, A. (Ed.), 1993, Water Resources Management in the Face of Climatic/Hydrological Uncertainties (in preparation).

Kaczmarek, A. & Krasuski, D., 1991, Sensitivity of water balance to climate change and variability, IIASA Working Paper, WP-91-047.

Keeling, C.D., Bacastow, R.B., Carter, A.F., Piper, S.C., Whorf, T.P., Heimann, M., Mook, W.G. & Roeloffzen, H., 1989, A three dimensional model of atmospheric CO_2 transport based on observed winds: 1. Analysis of observational data. In: Peterson, D.H. (Ed.), Aspects of climate variability in the Pacific and the Western Americas, Geophysical Monograph, 55, AGU, Washington, 165–236.

Klemes, V., 1985, Sensitivity of water-resource systems to climate variations, World Climate Report No. 98, WMO, Geneva.

Klemes, V., 1986, Dilletantism in hydrology: transition or destiny?, Water Resour. Res., 22(9), 177S–188S.

Klemes, V., 1990, Sensitivity of water resource systems to climatic variability. Proc. Canad. Water Resour. Association, 43 Annual Conf., Penticton, 233–242.

Klemes, V., 1991, Design implications of climate change. Invited paper. The First National Conference on Climate Change and Water Resources Management, Albuquerque, New Mexico, Nov. 5–7, 1991.

Klemes, V., 1992, Implications of possible climate change for water management and development. Invited statement published in: Water News (Canadian Water Resour. Association Newsletter, S2–S3, April 1992).

Konikow, L.F. & Bredehoeft, J.D., 1992, Ground-water models cannot be validated, Adv. Water Resour., 15(1) 75–83.

Kulshreshtha, S.N., 1993, World water resources and regional variability: impact of future changes, IIASA Research Report, RR-93-xx (in preparation).

Kundzewicz, Z.W., 1991, Water sciences at the threshold of the 21st century, Proc. Commemorative Symposium, 25 years of IHP, UNESCO, Paris, 159–167.

Kundzewicz, Z.W., 1993, Hydrological uncertainty in perspective. In: Kundzewicz, Z.W. (Ed.), New Uncertainty Concepts in Hydrology and Water Resources, Proc. Madralin Symposium, UNESCO Series in Water Resources, Cambridge University Press (in press).

Kundzewicz, Z.W., Kaczmarek, Z. & Priazhinskaya, V., 1993, Water systems performance criteria for changing environment. In Kaczmarek, Z. (Ed.), Water Resources Management in the Face of Climatic/Hydrological Uncertainties (in preparation).

Mayer, G., Masliev, I. & Somlyódy, L., 1993, An analysis on the impact of climate change on regional sensitivity of lake stratification, IIASA Working Paper (forthcoming).

McCabe, G.J. & Wollock, D.M., 1992, Effects of climatic change and climatic variability on the Thornthwaite moisture index in the Delaware river basin, Climatic Change, 20: 143–153.

Mearns, L.O., Gleick, P.H. & Schneider, S.H., 1990, Climate forecasting. In: Waggoner, P.E. (Ed.), op. cit.

Mimikou, M.A. & Kouvopoulos, Y.S. (1991) Regional climate change impacts: I. Impacts on water resources, Hydrol. Sci. J., 36(3) 247–258.

Miser, H.J. & Quade, E.S. (eds.), 1988, Handbook of Systems Analysis. Craft Issues and Procedural Choices, Wiley, 681 pp.

Mitosek, H.T., 1992, Occurrence of climate variability and change within the hydrological time series. A statistical approach, IIASA, Collaborative Paper, CP-92-05.

Nemec, J. & Schaake, J., 1982, Sensitivity of water-resource systems to climate variation, Hydrol. Sci. J., 27(3), 327–343.

Niemczynowicz, J., 1992, Water management and urban development (manuscript), UNESCO Conference on "Environment and Development", Paris.

Orlob, G.T., 1982, Introduction. In: Orlob, G.T. (Ed.), Mathematical Modeling of Water Quality, Wiley/IIASA, Chichester, 1–10.

Ozga-Zielińska, M., Brzeziński, J. & Feluch, W., 1991, Development of a meso-scale hydrological model for climate impact assessment, unpublished report.

Rogers, P.P. & Fiering, M.B., 1990, From flow to storage. In: Waggoner, P.E. (Ed.), op. cit.

Ryszkowski, L., Kędziora, A. & Olejnik, J., 1988, Critical ecological factors for a sustainable development of agriculture in Poland. Report commissioned by IIASA. Department of Agrobiology and Forestry, Polish Academy of Sciences, Poznań, 29 pp. + xxiv.

Salewicz, K.A., 1992, Impact of climate change on Zambezi river reservoirs. In: Minami, I. (Ed.), Global Water Use under Limited Water Situation, Proc. Regional Conf. IRCSA, Kyoto, 4–10 Oct. 1992, 970–980.

Schaake, J.C., 1990, From climate to flow. In: Waggoner, P.E. (Ed.), op. cit.

Schaake, J.C. & Kaczmarek, Z., 1979, Climate variability and the design and operation of water resource systems, WMO, World Climate Conference, Geneva, 12–23 February 1979, WCC/Overview Paper 12.

Schneider, S.H., Gleick, P.H. & Mearns, L.O., 1990, Prospects for climate change. In: Waggoner, P.E. (Ed.), op. cit.

Schwarz, H.E. & Dillard, L.A., 1990, Urban water. In: Waggoner, P.E. (Ed.), op. cit.

Sellers, P.J., Mintz, Y., Sud, Y.C. & Delcher, A., 1986, A simple biosphere model (SiB) for use within general circulation models, J. Atmos. Sci. 43(6) 505–531.

Somlyódy, L., Alonso, L.R., Fleit, E., Hultman, B., Matsui, S. & Olson, B.H., 1992, Water quality 2000: A look at the main issues to the end of the century and how IAWQ should respond to them, IAWQ Yearbook, 1992–1993, IAWQ, London.

Streeter, H.W., Phelps, E.B., 1925, Study of the pollution of natural purification of the Ohio River, U.S. Public Health Service, Washington, D.C., Bulletin 146 (reprinted 1958).

Szilágyi, F. & Somlyódy, L., 1991, Potential impact of climate change on water quality of lakes, IAHS Publ. No.

The Global 2000 Report to the President, 1980, The Technical Report, Vol. 2, U.S. Government Printing Office, 766 pp.

Varis, O. & Somlyódy, L., 1993, Potential impacts of climatic change on water quality of lakes and reservoirs (in preparation).

Verstraete, M.M., 1989, Land surface processes in climate models: status and prospects. In: Berger, A., Schneider, S. & Duplessy, J.Cl. (Eds.), Climate and the Geosciences: A Challenge for Science and Society in the 21st Century, Kluwer Academic Publishers, Dordrecht, 321–340.

Waggoner, P.E. (Ed.), 1990, Climate Change and U.S. Water Resources, Wiley, 496 pp.

World Meteorological Organization (WMO), 1989, Report of Conference on Climate and Water, Helsinki, 11–15 September 1989.

Yevjevich, V., 1963, Fluctuation of wet and dry years, Part I. Research data assembly and mathematical models, Colorado State University, Hydrology Paper No. 1.

Yevjevich, V., 1964, Fluctuation of wet and dry years, Part II. Analysis by serial correlation, Colorado State University, Hydrology Paper No. 4.

Eagleson, P.S., 1970, Dynamic Hydrology, McGraw Hill, New York.