

Climate change and water resources

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ABSTRACT The consideration of the impact of climate on water resources is placed in a wider context: the chain reaction associated with such an impact crosses the interfaces between climate, hydrology, water-resource systems and society. Each interface demands collaboration and exchange of information between specialists and assurance that current tools and approaches are appropriate for the new environment that may evolve. The chain reaction must be studied from start to finish if the final impact on water resources is to be assessed. Various points are presented for consideration at each stage.

Impact du climat sur les ressources en eau

RESUME La considération de l'impact du climat sur les ressources en eau est placée dans un contexte plus large: la réaction en chaîne associée à un tel impact comprend les domaines communs au climat, à l'hydrologie, aux systèmes de ressources en eau et à la société. Chaque domaine commun nécessite la collaboration et l'échange d'informations entre les spécialistes et l'assurance que les outils et approches actuels soient appropriés au nouvel environnement susceptible d'évoluer. La réaction en chaîne doit être étudiée du début à la fin si l'impact final sur les ressources en eau doit être évalué. Différents points sont présentés pour être considérés à chaque stade.

Introduction

The last ten to twenty years have seen a major change in the generally accepted view of climate and of climatology. In the past, considerations of climate concentrated on long-term steady-state conditions. Variations in space were studied and explained, but variations in time were seen more as interesting historical phenomena than as anything of particular importance for mankind in the present age.

This all changed in a remarkably short period of time when, in the 1970's, a greatly improved capability for modelling the global atmosphere combined with increasing evidence and concern for the

consequences for the atmosphere of man's activities. Some preliminary findings hinted at major changes in climate under certain conditions, others led to quite different conclusions. At times the former received considerable publicity and the scientific community recognized the need for broadly-based programmes of research and evaluation on the whole subject of climate and the potential impact of its variability and change on society. Many countries have established national climate programmes for this purpose. At the international level, the World Meteorological Organization (WMO) convened the World Climate Conference in February 1979 (WMO, 1979), with the support of UNEP, FAO, Unesco and WHO. This led later in the same year to the establishment of the World Climate Programme whose overall objectives are:

(a) to apply existing climate information for the benefit of mankind,

(b) to improve the understanding of climate processes,

(c) to monitor significant climate variations and changes.

The existence of climate variability has long been recognized, including even the possibility of quite significant variations over comparatively short periods of time. However, without any real means of predicting such variations, they were not seen as being of any great relevance to regional or national planning. Our ability to predict variations is still very limited and any predictions that are made are hotly debated. It is interesting to speculate on the cause of the current interest in climate variability and change. Certainly, the fact that man himself may be the cause of such variations, even changes, has given the whole question far greater importance and urgency.

If we had perfect knowledge and foresight of the situation, we may find that variations and changes in climate over the next 200 years are neither greater nor more sudden than those experienced during the last 200 years. It is theoretically possible, therefore, that current analytical and planning techniques are adequate for generations to come and there is no real need for concern or for major changes in the way we manage affairs. However, we have neither perfect knowledge nor perfect foresight. What is more, there is a very real possibility that man's actions will have significant negative effects on the climate. These we should try to predict, plan for and, above all, prevent wherever possible. Therefore, while the reasons behind the current concern over climate change and variability may be studied by those interested in the history and philosophy of science, society has every right to expect scientists, engineers and planners to take the subject itself with the utmost seriousness.

The basic needs of mankind are commonly taken to include food and drink, clothing and shelter, and security against physical harm. The provision of food and drink requires an adequate supply of water and security demands protection from flooding as well as from other threats to safety. Some of the most important, in fact probably the most important, impacts on society of climate variability and change are introduced through the water cycle. The hydrologist and the water-resource engineer therefore have a major role to play in studying and planning for these impacts and it is very important that such work be undertaken in a co-ordinated fashion at national and international levels.

Climate variability and change

A whole range of definitions can be presented with reference to climate variability and change. The following have been found useful in developing plans for water-related projects under the WCP (WMO, 1985a):

"Weather is associated with the complete state of the atmosphere at a particular instant in time and with the evolution of this state through the generation, growth, and decay of individual disturbances."

"Climate is the synthesis of weather over the whole of a period essentially long enough to establish its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state."

"Climate change defines the difference between long-term mean values of a climate parameter or statistic, where the mean is taken over a specified interval of time, usually a number of decades."

"Climate variability includes the extremes and differences of monthly, seasonal and annual values from the climatically expected value (temporal mean). The differences are usually termed anomalies."

Water-resource systems

The simple existence of a body of water does not define it as a "water resource". For it to be a "resource" it must be available, or capable of being made available, for use in sufficient quantity and quality at a location and over a period of time appropriate for an identifiable demand. There is therefore an important distinction to be drawn between hydrology and the study of water resources.

A water resource may already be used or it may represent only a potential for the future. In either case, its current and future reliability are important factors and a firm prediction of a future reduction in quantity or reliability may deny the use of the term "water resource". In this sense, therefore, a future climate change would not only affect the magnitude or reliability of existing water resources but it would also make available resources that had not previously been considered as such or result in the total loss of many existing resources.

The hydrologic cycle is an integral part of the climate system and is therefore involved in many of the interactions and feed-back loops which give rise to that system's complexity. Water-resource systems represent man's intervention in and use of the hydrologic cycle for his own benefit. Even the simplest are subject to a number of external influences each offering avenues for the impact of climate change. They contain many interactions within them and, on a local scale, can significantly modify the hydrologic cycle. Therefore, while water-resource systems may be viewed principally as the recipients of climate impacts, through the intermediary of the hydrologic cycle, they may themselves have an impact on climate, particularly where they are very large in scale or in number or where

the hydrologic cycle is in a delicate state of balance.

Any investigation of the interaction between the climate system, hydrologic cycle and water-resource systems must recognize the complexity of the relationships involved. As regards water-resource systems, one approach would be to first identify the various elements involved in each system and then to study the climatologic and hydrologic factors influencing the design and efficiency of operation of each such element. A systematic presentation of the various types of water-resource system and the hydrologic factors and techniques involved in the design and operation of each type was compiled under the auspices of the International Hydrological Programme of Unesco (1982). The emphasis of WMO's Operational Hydrology Programme is on the requirements of each type of project for hydrologic and climatologic data. These were considered by Andrejanov (1975) over ten years ago and a recent report (WMO, 1987) contains extensive tabulations setting out such requirements.

At this point in time, the principal demand is not for precise estimates of the potential impact of climate change on specific water projects, but for indications of the general nature and extent of such impacts on various types of water project. Each hydrologic factor of relevance and each data requirement represent an avenue by which climate change might have an impact on the type of project in question. Therefore, reports such as those referred to above offer a good basis for identifying not only the types of project to be considered but also the climatologic elements and their characteristics which are likely to be important in a study of the impact of climate change.

Needs for information on climate change

The distinction drawn above between "variability" and "change", while clear in principle, is by no means easy to apply in practice. Variability is not so difficult to recognize and assess, but in order to study the effect of climate change we must first be able to distinguish change from variability. The progress being made in this regard by both climatologists and hydrologists is to be noted and they should be encouraged to continue with their important work.

Likewise, encouragement should be offered to those climatologists and atmospheric physicists who study the climate system and seek to explain its variability and past changes and to predict its future behaviour. Their advice is vital to those concerned with the impact on water resources for, without some indication of likely future changes in climate, any discussion of impacts will be restricted to theory and be of limited practical value. However, the water-resource engineers and planners must be prepared to state clearly what advice they require. The climatologists and atmospheric physicists have legitimate interests of their own and, in addition, many other groups make requests of them for specific information to satisfy their own particular needs. It is not enough to express dissatisfaction with the form or content of current climate predictions, the hydrologist and water-resource engineer must clearly define their own needs and make them known by appropriate means.

This list of needs is likely to encompass such parameters as:

(a) Space scale: global; hemispherical; continental; regional; national; sub-national.

(b) Time scale: hundreds of years; tens of years; annual; seasonal; monthly.

(c) Elements: radiation (at ground surface); temperature; wind speed; precipitation; humidity.

(d) Characteristics: mean; variance; skew; probability of extreme values; spatial and temporal correlation; cycles; trends; abrupt discontinuities.

At present climate predictions concentrate on changes in the mean values of a few selected elements over periods of ten to twenty years on a global or hemispherical basis. It is not at all clear at first sight what characteristics of what elements are likely to be of greatest significance with regard to the impact on water resources. Precipitation is a prime candidate but, unfortunately, it is the element about which climate predictions say the least and say it with the least confidence. Similarly, while abrupt changes or trends in mean values are important, increased or decreased dispersion and/or probabilities of extreme values are likely to be far more critical. The mean precipitation and temperature may remain unchanged even within each season, but a modest increase in their variability could throw doubt on the viability of certain rain-fed crops or run-of-the-river hydropower schemes and could leave major reservoirs either empty or threatened by floods which are greater than those for which their spillways were designed.

If the types of water-resource projects are identified together with the climate characteristics that are significant for each then a list of climate prediction requirements might be drawn up. It may not be such a difficult task for an individual with a particular interest, but it will not be easy to obtain consensus on the matter among a group of experts viewing the problem from various national or regional perspectives. It is important that any such list be as short as possible and those concerned must realize that it will be many years before even a preliminary response can be made on some items. Despite these difficulties, it is important that this task be undertaken in an appropriate context at an early date. If it is not, then the climatologists and atmospheric physicists will not be able to take due account of hydrology and water resources in their investigations and the most important channel for climate impact may be poorly treated.

One last, but important, comment on this question: the identification of needs is likely to be a dynamic and iterative process. As each climate prediction is studied and as the likely impact on a particular type of water-resource system is assessed, new information about the sensitivity of the system to such changes will be acquired which will often lead to a request for more detailed predictions or predictions concerning additional parameters. The list of needs will therefore evolve and change with time, but until a first draft list is established, little progress can be made.

The impact of climate change on hydrology

The impact of climate change follows a chain reaction. As already

noted, the hydrologic cycle is part of the climate system and so the first link in the chain is the impact on hydrologic processes. Here the obvious approach is to use the hydrologic model as the basic tool, adjust various parameters and inputs to simulate climate change and study the model's response both as regards its state variables and output. Even given a specific prediction scenario, it is not easy to decide what adjustments to make to what; it is even more difficult to interpret the results when the scenarios used are as speculative as they are at present. Nevertheless the work that has already been done in this regard (e.g. Nemec and Schaake, 1982) is of great importance in that it has awakened interest in the hydrologic community to the whole subject and has laid the groundwork for future studies.

The more precise one wishes to be in any investigation, the more one should question the qualities and appropriateness of the tools used. Where the tool is inadequate for the task, the results can be of little value. Klemes (1985) has set very exacting standards for hydrologic models if they are to be used in this context. It is to be hoped that model developers will apply such tests so that any results obtained by using a model may be judged against the results of his or similar tests.

Alternative approaches which do not make use of hydrologic models have also been proposed. For example, studies in comparative hydrology are seen as offering a potential source of information. As with all analyses which trade variations in space for variations in time, these should be approached with caution. They can illustrate the types of equilibrium states that have been established in the past under various external influences. The question to be asked is how much they can tell us about the dynamic response of hydrologic systems when they are subjected to changes in time in climatic factors.

This first link in the chain also involves the interface between the atmosphere and the land surface. Inadequate modelling of the water and energy balances at this interface are held to be one of the factors which currently limit the performance of general atmospheric circulation models. It is on these models that many of our hopes depend for improved climate predictions. As hydrologists seek better predictions of climate variability and change, they should therefore be prepared to make a substantial input to the work of those who model the atmosphere. The basis for such collaboration has already been established and the work commenced (Eagleson, 1982; WMO, 1985b): a most welcome sign.

Hydrologic processes and water-resource systems

The second link in the chain is that between hydrologic processes and water-resource systems. As the systems are man-made it is easy to see this as a simple matter. The anticipated variations and changes in the climatologic and hydrologic processes can be introduced in the relevant parameters and time series inputs to mathematical models of the systems. The impact on their performance may then be investigated on the basis of the outputs and general system response. However, as mentioned earlier, the interaction between water-resource systems,

climate and hydrology may be more complex than at first expected. It may involve feed-back mechanisms and, in particular, significant changes in certain processes may cause the system to operate in a manner totally different from that experienced to date and may even result in the system being unable to serve any useful purpose. For example, a moderate increase in the probability of below-freezing temperatures would have a negligible influence in the hydrologic regime but could make it impossible to sustain the production of citrus fruits. Unless an alternative crop could be cultivated, the irrigation scheme serving the orchards would then be of little future value. In another situation, a shift in timing of the wet season may permit rain-fed agriculture where irrigation was previously essential. The more obvious examples are long term trends in mean values or changes in probabilities of extremes which could result in empty reservoirs or increases in water logging or the threat of flooding.

The interface between water-resource systems and the natural processes within which they are embedded is also complicated by the fact that, while the systems are man-made and hence reasonably clearly defined in physical terms, the manner in which they are operated is rarely so well understood and can change or be changed with considerable ease. The operating policy is one of the principal characteristics of a water-resource system. For some systems it may be possible to amend the policy so as to counteract or even take advantage of climate variability and change. For others, however, the freedom to change the policy may be very limited. The actual manner in which water-resource systems are currently operated is the result of a complex, even stochastic, balance of factors: physical, socio-economic, political and human. There is no reason to believe that this will not continue to be the case in the future and this complexity and uncertainty should always be borne in mind when evaluating theoretical optimum policies. Despite this, it is vital that a consideration of operating policies be included as a part of any water-resource system study.

Water-resource systems and society

The response to predictions and indications of climate change could be structural, such as an increase in the height of levee banks, the construction of new storage reservoirs or the installation of additional turbines. It could also be non-structural: the implementation of hydrologic forecasting systems to allow more optimal use of water supplies, revised operating policies for existing systems or changes in social habits and economic activity.

The third link in the chain, that between water-resource systems and society, is therefore of great importance and one that is dominated by feed-back mechanisms. Both the physical characteristics and the operating policy of a system are designed to meet the perceived needs of society in one way or another. A change in climate or a change in its variability could greatly affect these needs. Domestic and agricultural demands for water would be expected to increase if temperatures increase, but if this is accompanied by an increase in precipitation then agricultural demand may fall, depending on seasonal factors. If a significant change in climate is

predicted, farmers, industrial managers and the general public may respond in a manner analogous to the response seen during recent oil crises, and the net impact on society may be far less than anticipated. Conversely, a negative or ill-judged reaction could aggravate the situation and amplify the impact.

In one sense, the water-resource system, with all its imprecision, sits as a relatively well-defined entity linked on the one hand with the natural environmental systems of climate and hydrology and on the other with the socio-economic and political systems of man. This latter interface, the third in the series, is complex, dynamic, multi-faceted and, above all, difficult if not impossible to predict as regards its future characteristics and performance. Much valuable work has been done on the multi-objective planning of water-resource systems and various techniques have been developed for rationally accounting for competing demands expressed in financial terms or in various measures of public safety and welfare. In theory, these techniques should hold for the consideration of the impact of climate change, but in practice it is likely to prove vastly more difficult to express in concrete terms the desires and limitations of each sector under the predicted future conditions than under present circumstances. What will be the priorities of a society which is faced with a change in climate where this might lead to marked increases or decreases in temperature and precipitation, in food and water supplies, in health and safety risks and in the general quality of life? Where our hydrologic models need to be tested to ensure that they will yield valid results under conditions beyond those for which they were originally derived, so too will our socio-economic models. Strictly speaking, this is outside the subject of this paper, but it is certainly of relevance to the subject.

Hydrologists have long been concerned that hydrologic forecasts are adequately disseminated and correctly interpreted so as to ensure that they are of greatest value. Those who predict the response of water-resource systems to climate change should be equally concerned that their predictions could affect the validity of the predictions themselves. It is essential, therefore, that current efforts to involve the appropriate water users and decision makers in the planning and design of water-resource systems be taken much further in the study, planning and design of systems to respond to the impact of climate change. Without true dialogue, the predictions could include grave errors and the plans could prove very ineffective.

Concluding remarks

The purpose of this paper is not to review the current state-of-the-art in the study of the potential impact of climate change on water resources. Up until mid-1986 there were not so many published papers on the subject (Beran, 1986), but the field is gaining in interest and the papers presented at the current symposium should provide a good indication as to what has been achieved and what studies are planned for the future. The aim of the author has been to put the whole field of study into its wider context, to raise certain questions that need to be answered and to propose, in some instances, what approaches might be taken.

The past concentration on thirty-year normals has been replaced in climatological circles with the study of climate variability as an important and relevant topic. To this has been added the oft dramatic predictions of climate change, either man-made or resulting from natural causes. Even the more sober analyses and consensus (e.g. WMO, 1985c) indicate that the climate may well change to a degree and within a time frame which makes it important to take such a possibility into account in future planning of major projects. Of all the possible impacts of such change, the most important is likely to be that on water resources. Hence the importance of the whole subject considered in this paper.

The renewed interest in the climate system and its interaction with other natural systems is not solely related to climate change. Examples are international projects concerning the El Nino-Southern Oscillation and related phenomena which form part of the Tropical Ocean and Global Atmosphere Programme (WMO, 1985d). These promise to provide a more complete understanding of the climate system leading to an enhanced ability to predict climate variability quite apart from climate change. Such predictions have great potential value for the better management of current water-resource systems as they offer the hope of one day being able to forecast future water supplies over extended periods. It would be wiser, therefore, to think always in terms of predicting climate variability and not just change.

Nevertheless the principal topic of concern here is the impact of climate change and, to summarize the points made earlier, it would be valuable to:

- (a) categorize the important types of water-resource system;
- (b) identify the climatologic and hydrologic factors which affect the design and operation of such systems;
- (c) identify the climatologic characteristics which are likely to be important in a study of the impact of climate change;
- (d) offer all encouragement to those studying the climate system with a view to predicting future behaviour;
- (e) clearly define the needs of water-resource engineers and hydrologists for climatologic information relevant to possible climate change;
- (f) test the hydrologic models and other tools used to study the impact of climate change as a guide to the reliability of the results they yield;
- (g) contribute to the work of atmospheric modellers in their search for an improved representation of the atmosphere/land surface interface;
- (h) take account of the real nature of the water-resource systems being studied, in particular their operating policies;
- (i) pursue investigations as far as the impact on society so as to account for the complex and dynamic nature of the feed-back mechanisms which link water-resource systems to their socio-economic environment.

The above tasks will not be easily accomplished, but their achievement is likely to be of the greatest importance to the future well-being of mankind. Those who embark on this work should do so with a sense of purpose and caution; above all they should avoid sensational or ill-founded speculation but firmly and widely proclaim any findings and predictions which they see as being of importance for

the future planning and operation of water-resource systems.

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