1 Introduction

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1.1 PROBLEM IDENTIFICATION

The subject of UNESCO's International Hydrological Programme (IHP-IV) project H-2.1, 'Study of the relationship between climate change (and climate variability) and hydrological regimes affecting water balance components', is relatively new, but it is of vital importance for society. Climate change and variability will affect the hydrological cycle, which will in turn affect both the distribution and availability of water resources for domestic use, for food production, and industrial activities, as well as for the production of hydropower. Other hydrology-related aspects include flood control, water quality, erosion, sediment transport and deposition, and ecosystem conservation. Most uses of water are economically important, and thus are related to socioeconomic development, as well as to public health and well-being and the environment, which themselves are also interrelated. Thus the concerns over the potential impacts of climate change range from the causes to the ultimate and diverse social consequences, which will vary depending on the location and the human responses. This volume addresses mainly the impacts of climate change on hydrological systems, but occasionally some other aspects are also considered.

The social relevance of this study is well illustrated in the tentative statement formulated at a meeting of the Working Group, as follows:

The world’s population is increasing at an unprecedented rate, and this will have implications for many areas of human activity. According to the UN Conference on Population and Development, held in Cairo in 1994, the global rate of population increase is now about 1.6%, whereas for the continent of Africa the rate is as high as 2.8%. Moreover, the proportion of the world’s population living in urban areas is increasing rapidly, particularly in the less developed regions. There is now a consensus among scientists that the populations of arid and semi-arid regions are likely to be the most seriously affected by climate change. It is therefore of paramount importance to improve our understanding of how climates may change in the future, and of the various ways in which such changes will impact the populations of these regions.

Research in several areas of geology indicates that the climate has changed throughout the history of our planet. Information dating back many hundreds of millions of years has been obtained from the Earth’s geological archive, consisting of the subsoil of the Earth, glaciers and polar icecaps, and the remains of flora and fauna that serve as indicators of palaeoclimatic conditions. In contrast, quantitative records of meteorological and hydrological conditions of the past date back a few centuries at most. In between these two extreme time scales, much information has also been obtained from other sources, such as archeological and historical records of the past few thousand years, pollen analyses, and radiocarbon dating (Issar, 1995). The Historical Archives Climate Project is now being designed as a joint project of the World Meteorological Organization (WMO), UNESCO, the International Council of Scientific Unions (ICSU) and the International Council of Archives (ICA), with the objective of expanding our knowledge of climates in the past.

Over the long term, the climate of the Earth has changed due to a number of natural processes, such as gradual variations in solar output, meteorite impacts and, more important, sudden volcanic eruptions in which solid materials, aerosols and gases (sulphur) are ejected into the atmosphere. Ecosystems have adapted continuously to these natural changes in climate, and flora and fauna have evolved in response to the gradual changes in their physical conditions, or have become extinct. The rate of climate change over time has been a major determining factor in the possibility and type of adaptation, or extinction.

Humans have also been affected by and have adapted to changes in local climates, which have occurred very slowly. Over the past century, however, human activities have begun to affect the global climate. These effects are due not only to the population growth, but also to the application of technologies that have been developed for survival, to raise standards
of living, and, regretfully, also for non-peaceful purposes. The resultant changes in climate are relatively recent, but have occurred much more rapidly than those due to natural causes. The scale of the present climate forcing is unprecedented, and is due to emissions of greenhouse gases, deforestation, urbanization, and changes in land use and agricultural practices. The increased concentrations of the so-called greenhouse gases – carbon dioxide (CO₂), methane (CH₄), nitrous oxides (NOₓ), ozone (O₃) and chlorofluorocarbons (CFCs) – in the atmosphere is causing the air temperature to rise, as in a greenhouse, and this in turn is having many other effects such as changes in the rates of evapotranspiration and in the amounts and distribution of precipitation. Mankind will certainly respond to these changing conditions by taking adaptive measures, such as changing patterns of land use, although it is difficult to predict what adaptive measures will be chosen, and their socio-economic consequences.

Climate change does not necessarily imply that standards of living will fall. For example, increased CO₂ concentrations in the atmosphere may be beneficial for plant growth, thus enhancing agricultural production in some regions, which will have economic and social consequences. This partly explains the different degrees of willingness of various national governments to take action. The level of development of a particular country is another important factor in attitudes to this matter.

This section has outlined the problems and opportunities presented by climate change and variability, and some of the impacts on the hydrological cycle and consequently on water resources. Real world problems require research, so that the role of hydrologists, in cooperation with climatologists, is to describe the physical (meteorological and hydrological) processes in such a way that not only the past and present conditions can be simulated accurately, but that the future conditions can be predicted in terms of averages and frequency distributions for a number of primary climatic and hydrological variables and the derived parameters that can be used to characterize future changes in water resource systems across the globe.

1.2 THE CLIMATE SYSTEM

The climate system refers to the atmosphere, but there are close interactions with the seas and oceans and with the land surface, in terms of fluxes of energy, water and carbon dioxide. The atmosphere has only a small buffer capacity, but the oceans and, to a lesser extent, the glaciers and icecaps are gigantic buffers for heat and water. Thus there is a considerable time lag between the causes of climate change and their effects. Since natural changes in climate occur only very slowly, so also do their effects. Similarly, the full effects of the increase in the intensity of human activities will take some time to be felt on the human time scale, as will the benefits of any countermeasures that may be taken – such as changes in land use – in response to climate change.

1.2.1 Recent studies of climate change

In recent years awareness has been growing that the rate of climate change due to human activities is accelerating. This new realization is due to climate studies, based on meteorological observations over the past few centuries of increasing numbers and types of parameters. Most recently, the issue of climate change and its effects has been addressed by the Intergovernmental Panel on Climate Change in its first report (IPCC, 1990a), its summary for policymakers (1990b), followed by a supplement (IPCC, 1992), and the second IPCC report (IPCC, 1995).

1.2.2 Hydrological impacts of climate change

Climate change and variability has many effects on the hydrological cycle and thus also on water resources systems. Flood protection or water supply systems, both existing and planned, will be affected. These effects may not necessarily be negative, but they need to be anticipated as far as possible (Kaczmarek et al., 1996), because of the socio-economic consequences of the costs of construction, operation and maintenance of water control systems.

Changes in the hydrological cycle due to climate change, whether natural or human-induced, will also lead to changes in natural vegetation patterns, through desertification, the relative rise in sea level, etc. The human response is likely to be to change existing systems of land use, such as by introducing new crops or new cropping patterns with different water requirements, both in total and in their distribution over time. Any change in the hydrological cycle resulting from human responses to changing water resources systems will add to the interactions between the climate and the hydrological cycle. The impacts of human responses on the hydrological cycle are even more difficult to predict than those of climate change.

The planning and construction of water supply systems, coastal protection structures, dikes, etc., take many years, and the lifetimes of such structures are of the order of a century. It is therefore necessary to design them according to criteria that relate to the future, a century ahead, that is, during and after the present period of climate change.
The assessment of climate change and its likely impacts on the hydrological cycle is extremely complex. Hydrologists have to deal with several time scales, varying from periods of several years in dealing with problems of reservoir operation or groundwater levels, to periods of the order of 5–15 minutes in dealing with urban runoff and the capacity of sewerage systems. Intermediate between these two, floods can occur on time scales of days to weeks. Hydrologists therefore need to be informed by climatologists about annual or monthly values (means and standard deviations) of relevant parameters such as precipitation and evaporation (or the underlying climatic variables), and they also need to have detailed statistics of various events or intervals of short duration.

Climate change and variability are occurring at the global or continental levels, i.e. at areal scales that are much larger than those at which hydrological problems are encountered. The impacts are usually felt over areas larger than individual countries or even international river basins. Studies of the relationship between climate change and variability and hydrological regimes therefore need to be international.

The effects of sea level rise due to climate change on the hydrological cycle may be particularly acutely felt in coastal zones. Apart from the loss of land, the regimes of the downstream reaches of rivers, deltaic areas and estuaries are likely to change, and consequently also the distributions of fresh and saline water, both in surface water and in groundwater.

1.3 STATE OF THE ART OF MODELLING

1.3.1 Integrated models

Modelling the hydrological impacts of climate change involves two issues: climate change and the responses of hydrological systems, or rather their mutual interaction. So far, there is no integrated atmosphere-hydrosphere model that can simulate hydrological phenomena at the basin scale for given scenarios taking into account the feedbacks between climate and hydrology. Whether desirable or not, so far it has not been possible to develop such an ‘ideal’ integrated model for a number of reasons:

- the spatial scales of existing climate models are too coarse to allow for a proper fit to the areas to which hydrological models are commonly applied; as a consequence,
- representations of interactive processes can not yet be properly included in such models, and even if they could,
- the computer time required would make such models impractical.

Two kinds of models are used: the so-called general circulation models (GCMs) to model climate, and hydrological models.

1.3.2 General circulation models (GCMs)

GCMs are used to obtain descriptions of current atmospheric processes. At present, there are only a handful of such models, because they require considerable effort to build, and they can only be implemented and run on very large capacity computers. The few large research institutions that have developed and applied such models include (in alphabetical order)

- the Canadian Climate Center (CCC);
- the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia;
- the European Centre for Medium-Range Weather Forecasting (ECMWF), Reading, UK;
- the Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ, USA;
- the Goddard Institute of Space Sciences (GISS), USA;
- the Laboratoire du Météorologie Dynamique (LMD), Paris, France;
- the Max Planck Institute (MPI), Germany;
- the Meteorological Research Institute (MRI), Japan;
- the National Center for Atmospheric Research (NCAR), Boulder, CO, USA;
- Oregon State University (OSU), OR, USA;
- the United Kingdom Meteorological Office (UKMO), Hadley Centre, Bracknell, UK.

The areas modelled by GCMs are subdivided into grid cells with horizontal dimensions of the order of 300 × 300 to 1000 × 1000 km². In the vertical direction, the Earth’s atmosphere is subdivided into six to ten or more layers, each several hundred metres thick. The temporal resolution is of the order of 30 minutes to 1 hour.

Recently, regional circulation models (RCMs), with grid cells of the order of 50 × 50 km², have been developed for application to relatively small regions, using inputs from GCMs. Obviously, the resolution of an RCM for a particular region is better than that of a GCM.

The atmospheric processes modelled in RCMs are based on mathematically formulated physical laws. The various GCMs differ not only in their grid sizes and the number of layers, but also in the number of processes and relevant parameter values that can be included. A weak point of
most GCMs is their inability to model properly the physics of clouds; in this respect the various GCMs vary consider-
ablely, and often produce quite different results.

The presence and effects of aerosols originating from human activities and volcanic eruptions are not yet included in the present GCMs, even though there are strong indications that carbon-containing aerosols can have a great influence on climate (Mitchell et al., 1995).

According to ten Brink (1996), ‘the direct reflection of sunlight by anthropogenic aerosols in western Europe is larger than the (enhanced) greenhouse effect’. Since ‘dust particles’ compensate for the greenhouse effect, there is clearly a need for further research on the presence and effects of aerosols.

In GCMs the important elements are the interactions between land and water surfaces, and the fluxes of energy, water and CO₂. The descriptions of these processes, for large areas, are often based on small-scale field data or models that cannot be valid for such large grid sizes. This problem of upscaling is another reason for the differing results of GCMs.

1.3.4 Coupling of GCMs and hydrological models

The output from GCMs is still not good enough for the purposes of hydrological modelling, for the reasons explained above. There has been some progress in the mod-
elling of clouds and atmosphere–ocean interactions. Atmosphere–land surface interactions are still important areas of research, again because of problems of scale. The grid cells of GCMs are generally much larger than most of the basins in which the interactions between the atmosphere and hydrological cycle are studied by water balance. This means that there is a problem of regionalization or upscaling of the fluxes obtained from hydrological basin studies for use as inputs to GCMs, and/or of downscaling the results of GCMs to individual basins (Feddes et al., 1989; Feddes, 1995). The problem of scaling has long been recognized, and exists independently of climate change. A better under-
standing of the interactive processes that result in fluxes is therefore essential for better modelling.

1.3.5 Field experiments

The problem of coupling GCMs and hydrological models is currently being addressed in a number of field experiments on various scales, many of which involve international coop-
eration. Most of these experiments apply remote sensing techniques, the high resolution of which, and the improved correlation between the relevant information on land surface conditions and fluxes, offer good prospects for resolving the problem of scaling. Some of these experiments are briefly illustrated in the following; more complete descriptions, including the results obtained so far, are given for each con-
tinent in the relevant chapters in this volume.

- The Hydrologic-Atmospheric Pilot Experiment – Modélisation de Bilan Hydrique (HAPEX-
MOBILHY), conducted during 1986 in southwest France. This first large-scale field experiment (Shuttleworth, 1987) provided simultaneous detailed measurements of weather and surface flux variables over agricultural and forested areas. Aircraft and satel-
ellite remote sensing data were used for integration to a larger scale.
- The Hydrologic-Atmospheric Pilot Experiment-Sahel (HAPEX-Sahel and HAPEX-Niger) is a similar large-
scale experiment that is being conducted in the semi-
-arid belt of Africa. Here too, remote sensing techniques have been applied.
- Within the framework of the International Satellite Land Surface Climatology Project (ISLSCP), the First
ISLSCP Field Experiment (FIFE) was undertaken in
1987–88 in Kansas, USA (Shuttleworth, 1987). It also included satellite data.

- The Anglo-Brazilian Climate Observation Study (ABRACOS), undertaken jointly by British and Brazilian institutions in 1990–94, comprised several small-scale experiments in Brazil but did not include remote sensing data.

- The Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA),* to commence in 1997, will use remote sensing techniques to examine the tropical climate of the Amazon basin.

- The Biosphere-Atmosphere Transfers and Ecological Research In situ Studies in Amazonia (BATERISTA) can be regarded as a complement to the LBA for calibration and validation of the models developed within the LBA experiment.

- Within the Global Energy and Water Cycle Experiment (GEWEX), GEWEX Continental-scale International Projects (GCIPs) will be conducted in the Mississippi River basin (USA) and in the cold region of the Mackenzie River basin (Canada), the Mackenzie GEWEX Study (MAGS).

- Within the European Programme on Climate and Natural Hazards (EPOCH), there is a European International Project on Climate and Hydrological Interactions between Vegetation, Atmosphere and Land Surfaces (ECHIVAL). In the regional ECHIVAL Field Experiment in Desertification-Threatened Areas (EFEDA), now being conducted in central Spain, remote sensing and field data on soil moisture will be related to obtain average areal values.

In the implementation of the GEWEX Continental-scale International Project (GCIP) and the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA), a catchment approach will be adopted. The LBA (LBA, 1996) will incorporate a nested drainage basin approach (NDBA; Bonell and Balek, 1993) in order to address the problem of scaling from the micro-, through the meso-, to the macroscale. The NDBA concept, which is the product of a formal agreement between UNESCO’s IHP and IGBPBAHC, is described in more detail by Dunne and Barker (1997).

1.4 RELATED ACTIVITIES

Many international governmental and non-governmental organizations are collaborating in a wide variety of research programmes on or related to climate change. The jargon and the acronyms used by these organizations and their research programmes may make it difficult for outsiders to find their way through this labyrinth. Figure 1.1 gives an overview of these programmes and how they are interrelated. Explanations of the many acronyms used in this field are given in the Appendix.

The most important activities are those of the IPCC, as noted in Section 1.2.1. The WMO has undertaken a number of relevant initiatives (Lemmelä et al., 1990; WMO, 1985a, 1989a,b, 1990), and in 1980 launched the World Climate Research Programme (WCRP), with WCRP-Water as one of its sub-programmes. Within UNESCO’s IHP-IV programme, a related project (H-1.1) is a ‘Review of the scientific aspects of the interface processes of water transport through the atmosphere-vegetation-soil system at an elementary catchment and grid size scale’.

In 1987 the International Association of Hydrological Sciences (IAHS) held a symposium on the subject (Solomon et al., 1987), and set up an International Committee on Atmosphere, Soil and Vegetation Relations (ICASVR, 1992), which operates in cooperation with the H-1.1 project of UNESCO’s IHP-IV programme and the International Geosphere–Biosphere Programme (IGBP), a joint programme of the ICSU and the WCRP of the WMO (IHP-ICASVR-IGBP, 1995).

One of the core projects of the IGBP in cooperation with the WCRP is the Biospheric Aspects of the Hydrologic Cycle (BAHC). The activities undertaken within this project, in

Figure 1.1 Overview of international organizations and their research programmes (modified from Zwerter et al., 1995).

* The recently renamed LBA incorporates the formerly independent experiments LAMBAD (Large-scale Atmospheric Moisture Balance of Amazonia using Data Assimilation), BATERISTA (Biosphere-Atmosphere Transfers and Ecological Research In Situ Studies in Amazonia), and AMBIACE (Amazon Ecology and Atmospheric Chemistry Experiment).
particular those concerned with the relationships between Soil, Vegetation and Atmosphere (SVAT), are relevant to the ongoing projects described in this volume.

Among the multitude of activities and relevant publications, the following are of interest:

- the proceedings of the International Climate Change Research Conference, held in Maastricht, the Netherlands, in 1994 (Zwerver et al., 1995);
- evaporation modelling (Tallaksen and Hassel, 1992);
- an assessment of the impacts of climate change on tropical rainforests (Hulme and Viner, 1995); and
- possible impacts of climate variability and change on tropical forest hydrology (Bonell, 1998).

In particular, Bonell (1998) reviews the impacts of the conversion of forests to other land uses, under socio-economic pressure, in humid and semi-arid tropical regions - a subject that has been largely neglected so far. The paper describes controlled experimental studies in small catchments in the Amazon basin, Australia, India and the Sahel region of Africa. The effects of such changes in land use are compared with those of past natural changes in climate. The problem of the linkage between microscale hydrological results and the coarse resolution of atmospheric global climate models is recognized as a ‘trans-science’ problem. The paper also provides an extensive list of references.

In a broader context, some other projects are being conducted at an even higher level of abstraction:

- The IGBP project on Global Analysis, Interpretation and Modelling (GAIM). Its objectives are: (1) To propose and facilitate experiments with existing models or to link sub-component models, especially those associated with IGBP Core Projects and with the efforts of the World Climate Programme. Such experiments will be focused on resolving interface issues and questions associated with developing and understanding the prognostic behaviour of key processes. (2) To clarify the key scientific issues faced in the development of Global Biochemical Models and the coupling of these models to General Circulation Models.
- The Integrated Model for the Assessment of the Greenhouse Effect (IMAGE), developed by the Netherlands National Institute for Public Health and Environmental Protection (RIVM), consists of several submodels that can be used to study the consequences of various scenarios for emissions and land use. The RIVM has also launched the project Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions (ESCAPE).

1.5 SCOPE AND STRUCTURE OF THIS VOLUME

The mission of the Working Group on IHP-IV Project H-2.1 has been to compile information on the ongoing large-scale studies of the relationships between climate change (and variability) and hydrological regimes, their potential effects on water balance components, and to report on the results obtained so far.

This volume is relevant to the international community of scientists and practitioners of hydrology and climatology. It gives an overview of the climatic and hydrological changes that are already occurring around the world, and surveys the variety of methods that are being used to forecast future changes. Such a survey can of course never be complete, but it summarizes the areas for which information was available and accessible. It is clear that there are still large gaps that need to be bridged between the temporal and areal scales of resolution used in the modelling of atmospheric and hydrological phenomena and in the respective methods of study.

The preparation of this volume partly coincided with that of the second IPCC report, and some members of the Working Group and external assessors were involved in both. The two reports are quite different in nature, however. This report is restricted to the hydrological aspects of climate change and their consequences for water resources, and deals in particular with the various methods of ‘trans-science’ (hydrology and climate) research and their inherent problems. It therefore complements the IPCC report; there is little overlap and there are no major contradictions.

As the subject area is rapidly expanding, the prime contribution of the book is to provide a framework for synthesizing many diverse trains of thought, research and practice. This includes providing a connection between historical contemporary climate variability, future climate change impacts; and the various large-scale experiments for improving our understanding of climate regimes and hydrologic responses.

The effects of sea level rise on the hydrological cycle due to climate change may be considerable, as mentioned in Section 1.2.2, but are beyond the scope of this volume.

The structure of this volume is as follows: Chapter 2 provides an overview of the work of the IPCC in the period 1988–94.

Chapters 3–7 deal with the conditions and situations in South America, North America, Europe, Africa, and Asia and Australia, respectively. Although the titles of these chapters are similar, their contents differ considerably, partly because the conditions and situations in each of the continents
are different, and partly because the methods of study used are determined by the level of organization and the financial support allocated to such studies. These chapters were written by members of the Working Group, in some cases in collaboration with co-authors. All of the authors are either from, or have been involved in studies in the respective continents.

Chapter 8 is unique in that it gives a concise overview of the models that are being used in the evaluation of the impacts of climate change on hydrology.

Finally, Chapter 9 presents the conclusions and recommendations of the Working Group.
2 Climate change, hydrology and water resources: The work of the IPCC, 1988–94

I. A. SHIKLOMANOV

2.1 INTRODUCTION: PURPOSE AND OBJECTIVES OF THE IPCC

In the near future significant changes in the global climate can be expected, with an increase in mean air temperature of 3–4°C. For the northern temperate regions and high latitudes in particular, these changes are likely to affect a wide variety of physiographic features over vast regions, human living conditions, socio-economic structures and development, and natural ecosystems. The effects of a rise in global air temperature could be devastating: extensive melting of the polar icecaps and the resultant rise in sea level would impact coastal areas, and changes in atmospheric circulation would affect agricultural productivity and food supplies, as well as water resources in many countries.

In the early 1970s some scientists first warned of the possible impacts of human activities on the global climate (Budyko, 1972) and predicted a warming of 1.5–2°C in the coming decades. At that time, however, few climatologists supported the view that significant climate warming would result from increased concentrations of CO₂ in the atmosphere. On the contrary, it was widely believed that climate cooling would occur, and such a cooling trend was observed during the 1970s, according to data from the world meteorological network. Nevertheless, the first World Climate Conference (WMO, 1979) concluded that the human impacts on climate were serious, and that the problem required further study, but noted that science could not give a definite answer to the question of whether climate warming or cooling would occur.

The situation changed rapidly in the 1980s, when observation data showed a sudden rise in global air temperature. In 1985, the international conference on climate change and its impacts, in Villach, Austria, concluded that an increase in greenhouse gas concentrations during the first half of the next century would cause an unprecedented rise in mean global air temperature. The conference accepted the forecasts made on the basis of the recently developed general circulation models (GCMs), that a doubling of CO₂ (and minor greenhouse gases) in the atmosphere could cause global warming by as much as 1.5–4.5°C by the year 2030. The conference therefore called for further studies to assess the likely negative impacts of global warming on social, economic and ecological systems, and to formulate measures to prevent and/or to mitigate them.

By the late 1980s the problem of climate change and its possible impacts had become an issue of global concern. Noting the anxiety of scientists, international organizations and some national governments, the World Meteorological Organization (WMO) and the UN Environment Programme (UNEP) established in 1988 the Intergovernmental Panel on Climate Change (IPCC), headed by Professor Bert Bolin. The Panel was charged with the following: (a) to assess the scientific information on various aspects of climate change, such as emissions of major greenhouse gases and the resultant modification of the Earth’s radiation balance; (b) to use that information to evaluate the environmental and socio-economic consequences; and (c) to formulate realistic response strategies.

The IPCC began its task by establishing three working groups, with the following responsibilities: WG-I was to compile all the available scientific information on climate change; WG-II was to assess the potential environmental and socio-economic impacts of climate change; and WG-III was to formulate response strategies. A special committee was also set up to promote, as quickly as possible, the full participation of developing countries (IPCC, 1990a).

2.2 ORGANIZATION OF THE WORK OF THE IPCC

The work of the IPCC has proceeded in several stages. The first stage began in 1988, and was completed in October 1990 with the submission of reports to the Second World Climate Conference in Geneva (IPCC, 1990b). In the second stage,
1991–92, a supplementary report was compiled containing updated data (IPCC, 1992). In 1993 the work of the IPCC was extended to include more specialists from different countries. The preliminary findings of the third stage of the IPCC’s activities were considered in late 1994, and the final report was published in summer 1995 (IPCC, 1995).

At each stage, the IPCC’s WG-II has been concerned with assessments of the potential impacts of climate change on hydrological regimes and water resources, including problems of water management, consumption and utilization, water availability, and the protection of water supplies. At the first stage, WG-II was headed by co-chairmen Dr G. Lins (US Geological Survey), Professor I. Shiklomanov (Russian State Hydrological Institute), and Dr E. Stakhiv (US Corps of Military Engineers). Dr M. Kara (Algeria) was nominated to represent the developing countries. These specialists prepared a chapter on hydrology and water resources for the report of WG-II (Shiklomanov et al., 1990), submitted a report to the Second World Climate Conference (Lins et al., 1991), and later published a supplementary report on the impacts of climate change on hydrology and water resources (Stakhiv et al., 1992).

During the second stage, two groups of specialists were set up to assess the impacts of climate change on freshwater systems, and to prepare two chapters for the IPCC’s final report. The first group, headed by Professor H. Lang (Switzerland), with members B. Bates (Australia), Chunzhen Liu (China), S.K. Mugera (Kenya) and O. Starosolszky (Hungary), was to prepare Chapter 10, on hydrology and freshwater ecology. The second group, headed by Professor Z. Kaczmarek (Poland), with members N. Arnell (UK), E. Stakhiv (USA), K. Hanuki (Japan), G. Mailu (Kenya) and L. Somlyody (Hungary), prepared Chapter 14, on water resources management. These materials were used in the preparation of the present report.

2.3 MATERIALS

The task of the IPCC was not to conduct research on the problem in different regions, nor to prepare long-term scientific programmes and outlines, but to gather together the results of research conducted in various countries. The Panel was then to generalize the results from the scientific viewpoint, to prepare proposals for future research, to develop practical recommendations, and to bring the results to the attention of international organizations, decision makers and the public. To meet its objectives, the IPCC needed to consider as much material as possible from different physiographic regions, reflecting the different socio-economic conditions in all continents, in both developed and developing countries.

The materials used in the preparation of the IPCC’s reports on hydrology and water resources were as follows:

- Special surveys summarizing the research of individual authors in their own countries, including up-to-date unpublished materials. Detailed reports were also prepared for some other countries, such as Belgium, Germany and New Zealand.
- Materials prepared by international organizations, and the proceedings of international meetings, such as the symposium on the impacts of climate variability on hydrological regimes and water resources (Vancouver, Canada, 1987), the US-Canada symposium on the effects of climate change on the Great Lakes basin (1988); the conference on climate and water (Helsinki, Finland, 1989); and the conference on the effects of climate change on the environment and society (Japan, 1991). Extensive information was also obtained from the proceedings of national symposia in Australia, the USA, etc.
- Reports published in the previous ten years by various national and international organizations; these were the most accessible sources of information for the IPCC reports, which cite more than 600 references.

The IPCC also used the reports of studies conducted for river basins and regions in the following countries (in alphabetical order): Algeria, Argentina, Australia, Bangladesh, Belgium, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, Hungary, India, Indonesia, Israel, Japan, Kenya, Nepal, The Netherlands, New Zealand, Norway, Peru, Poland, Romania, Russia (former Soviet Union), Senegal, Sweden, Switzerland, Thailand, UK, Uruguay, USA and Venezuela. The continents of Australia, Europe and North America have been most completely investigated, whereas Africa and some regions of Asia and South America have been only poorly studied.

2.4 SCENARIOS AND METHODOLOGICAL APPROACHES

Until recently, forecasts of anthropogenic climate change have been unreliable, so that scenarios of future climate conditions have been developed to provide quantitative assessments of the hydrological consequences in some regions and/or river basins. These scenarios can be classified into three groups: hypothetical scenarios, climate scenarios based on
GCMs, and scenarios based on reconstructions of warm periods in the past (paleoclimate reconstructions).

**Hypothetical scenarios** are based on arbitrary specified changes in future climate characteristics. In most of these scenarios it is accepted that air temperature will rise by 0.5–4°C and that precipitation will change (rise or fall) by 10–25%. Some authors also specify hypothetical changes in evaporation. In some reports scenarios have been specified proceeding from analyses of changes in climate characteristics that occurred in the past during particularly warm or cold periods of hydrometeorological observations. Using hypothetical scenarios that are not related to a particular time in the future, it is possible to assess the probable responses of a river basin to certain changes in climate parameters. These hypothetical scenarios were applied mainly in the early stage of research in the 1980s, but are now only rarely used.

**Climate scenarios** are based on the results of the computations of GCMs, several of which have been developed. The GCMs most often used to assess the hydrological consequences of climate change are those of the US Geophysical Fluid Dynamics Laboratory (GFDL), the Canadian Climate Centre (CCC), and the UK Meteorological Office (UKMO). Other widely applied models include the GISS, OSU and NCAR models (USA), and the model developed at the Max Planck Institute (Germany). The first three models were performed by the IPCC’s WG-I (IPCC, 1990b); they provide the highest resolution, and consider the case of a doubling of atmospheric CO₂ concentrations by the year 2050. Recently, some GCM scenarios have been generated based on CO₂ increases of 10%, 20% and 30%.

GCM-based scenarios can provide details of changes in regional climates (monthly data on air temperature, precipitation, and other parameters) for almost all areas on Earth. At present, however, the results of such scenarios are not very reliable; different GCMs often provide different and even contradictory results even for the same region, on precipitation in particular. This is very important for assessments of hydrological consequences. The results of GCM-based and hypothetical scenarios for the same regions are also often different (at least in the case of precipitation).

**Paleoclimate scenarios** are based on the use of climates in the past, when concentrations of CO₂ in the atmosphere were higher than at present, as prototypes of future climate conditions. For example, Russian climatologists (Hydrometeorozidat, 1987; Budko, 1988) showed that the so-called Holocene optimum (about 5000–6000 BC) might be regarded as a prototype of global warming by 1°C (in about 2000–2005); the last interglacial period 12 500 years ago (the Mikulskian interglacial) as a prototype of global warming by 2°C (2020–2025); and the so-called climate optimum of the Pliocene of several million years ago, when mean air temperatures were 3–4°C higher than today, might serve as a prototype of climate conditions in the more distant future (2040–2050).

Charts of the approximate distribution of the expected changes in air temperature and precipitation are available for the northern and southern hemispheres for each of these prototypes. These charts were obtained using various indirect methods and are accepted as the basis for assessments of the hydrological consequences of climate change. The most detailed charts were prepared for the former Soviet Union, and have been widely applied by Russian hydrologists. Such assessments have been made for river basins in Russia, as well as in South America (Budyko et al., 1994), and as a first approximation for the continents on average (Shiklomanov and Babkin, 1992). Scenarios based on paleoclimate data have also been developed for New Zealand (Griffiths, 1989).

The use of paleoclimate prototypes is very promising in that they allow consideration of possible variations in water resources within definite time intervals in the future, including the next 10–15 years. At the same time, this method presents some evident difficulties and constraints associated with, first, conventions regarding accepted climate prototypes in the remote past and future, and second, by the lack of reliable paleoclimate data for many regions. An assessment based on a paleoclimate reconstruction may therefore be regarded as just one possible version of the climate situation in the future.

Where climate scenarios are available, the quantitative assessments of the hydrological consequences of climate change analysed in the IPCC reports use the following sets of methods:

1. statistical dependencies between runoff and meteorological characteristics for the periods of observation;
2. long-term water balance for the periods of observation;
3. direct use of GCM computations; and
4. deterministic hydrological models for river basins for short time intervals.

The first and the second sets of methods have been widely applied by WG-II, especially during the first stage of research in the 1980s, because of their simplicity and the low input data requirements. However, the reliability of analyses using these approaches is low, especially with respect to changes in hydrological regimes over short time intervals (months, 10-day periods). It is difficult to apply these estimates to evaluate extreme characteristics of river runoff, so that statistical