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Needs for Climate Information in Support of Decision-Making in the Water Sector

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Abstract

As the fundamental drivers of the hydrological cycle are affected by increasing climate variability and climate change, the need for climate information for effective decision making in the water sector is crucial. Water resources management is essentially bounded by how the extremes – floods and droughts – are defined and characterized, along with methods and standards for reducing the risks to society. The ways in which water managers can adapt to contemporary climate variability, and which ultimately will serve as the foundation to adapting to climate change are described. Water managers use various surveillance, monitoring and assessment systems. Numerous variations of Decision Support System (DSS) tools have been developed by the water sector to assist in policy formulation, design, planning and operation of water infrastructure and some examples are given. The socio-economic factors that affect decision making, the mechanisms for interacting with stakeholders and water governance are described. Adaptation to current climate variability and potential climate change is a prerequisite for sustainable development and poverty reduction and needs to be integrated into the broader water resources development and management processes. Potential adaptation strategies in the water sector are described with examples. The needs for tailored climate products and services for the water sector are described. The major gaps in observations of climate change related to freshwater and hydrological cycles and the requirements for research and technology as well as for infrastructure, education, training and capacity-building are highlighted.

Keywords: Surveillance, monitoring and assessment; Decision support system tools; potential adaptation strategies; climate products and services.

1. Introduction

1.1 The issues

Water is the primary medium through which increasing climate variability and climate change will manifest itself and impact people, ecosystems and economies; affect sustainable development; and jeopardize economic development and poverty reduction efforts. As the fundamental drivers of the hydrological cycle are affected by increasing climate variability and climate change, they will have large impacts on water resources availability and demand. These changes in water availability and demand will exacerbate existing issues in sectors such as health, food production, sustainable energy and biodiversity.

The Intergovernmental Panel on Climate Change [1] states that water resources management clearly impacts on many other policy areas (such as energy projections, land use, food security and nature conservation). Increased water related risks associated with the changes in frequency of extreme events, such as flash floods, storm surge and landslides, will put further stresses on these sectors. It is critical to understand the processes driving these changes, the sequences of the changes and their manifestation at different spatial and temporal scales.

Water resources management is essentially bounded by how the extremes – floods and droughts – are defined and characterized, along with methods and standards for reducing the risks to society. Some estimate of the historical extreme events is necessary as the probabilistic basis for design for virtually all major physical infrastructure, and for setting flood and crop insurance rates, defining flood plain zones and designing storm sewers and highway culverts. In most cases the extremes and changes we are experiencing are still within the norms of natural historical climate variability as these infrastructures were designed to accommodate such order-of-magnitude variability.

At the input end, climate determines how much water is available (supply) and, with respect to use, how much water we need (demand) in the short and long term. A key feature of the climate is not necessarily the amount of rainfall or evaporation but the variability in these parameters from year to year and season to season. The erratic climate is most visible in the cycle of extreme events such as floods and droughts. Hence, climate variability and climate change will shape the nature of water availability.

There are also a range of other related drivers that affect water availability, distribution and quality. These include land use, vegetation, geography, groundwater–surface water interactions, ecosystems, urbanization and water management structures. All these factors add to the complexity of water management decisions, particularly in contemporary, publicly open and transparent decision processes.

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There is, however, an important duality in any approach that deals with climate uncertainties and their effects on the uncertainties in water availability – it must also deal with future uncertainties in population growth; technological development and rates of adaptation; economic growth and development; and human behavioural adjustments to scarcity. There are many positive and negative feedbacks as the two interacting streams of supply and demand adjust to both foreseen and unforeseen changes and surprises. Needless to say, demand factors and technological adaptation have played a much larger role than climate factors in most situations (except, perhaps in areas that are mostly dependent on natural rainfall, such as the Sahel), even though the climate-related supply/availability factors are much more uncertain.

1.2 The questions

The inherent nature of climate change is that it represents a relatively slowly evolving but highly uncertain phenomenon, the annual and interannual effects of which may be locally abrupt and severe. These changes are difficult to discern, much less predict, through the noise of climate variability and cyclic trends that are still not well understood, along with their potential, and sometimes catastrophic impacts on society and water management. In particular, both the physical effects of climate change, and their impacts on society are marked by a cascading concatenation of large uncertainties. Naturally, this greatly complicates decision-making in water management, particularly for large-scale water management infrastructure, the design of which is dependent on assumptions based on climate stationarity.

In order to address the issue of climate information needs for water resources decision-making, one must understand the nature of those decisions. Even within the bounds of historical climate variability there are difficult decisions that routinely surround basic management actions. The complexity of these decisions will inevitably be compounded with global warming because a great deal more uncertainty is introduced into the decision-making process. The expanded uncertainties and unknowns associated with global warming make such decisions and public participation even more daunting.

In any given region or location, planners and designers have to determine a broad set of related issues that are always dependent on the frequencies of hydrologic and precipitation phenomena:

(a) What are the impacts of changes to land/vegetation cover under different climate change scenarios, and what vegetation replacement patterns are a result of climate change?

(b) What is the extent of resilience of groundwater sources to short- and long-term climate change patterns?

(c) What are the effects of precipitation variability on rainfed agriculture and the occurrence of wildfires?

(d) How can coastal freshwater systems (surface and groundwater) be maintained in light of rising sea levels and saltwater intrusion?

(e) What are the effects of shrinking glaciers on freshwater ecosystem and irrigation systems?

(f) How much storage in a reservoir should be allocated to irrigation versus other competing future needs?

(g) How should spillways be sized for rare floods?

(h) How high should a levee be, and what is the risk to those living and working behind it?

(i) How should a 100-year flood plain be characterized and identified?

(j) How should a reservoir be adaptively managed to accommodate an increasingly uncertain spring runoff?

(k) What criteria should be used to “recertify” flood mitigation structures where the flow frequencies have changed or are in the process of changing?

(l) How should our contemporary ideas on life cycle infrastructure management and performance and our shifting towards the wiser use of natural ecosystem infrastructure accommodate our evolving scientific understanding of climate change?

(m) What discount rate should be used for benefit-cost analysis?

(n) What flood frequency distribution should be used in a particular analysis?

(o) What are the benefits and costs of storm water harvesting, water recycling, water efficiency, desalinization and in the management of drought?

If the paradigm of climate stationarity is indeed defunct (still open to debate), then a new family of theories and tools must be developed to assist water sector decision-making. In the absence of such a new class of tools, coupled with the large uncertainties inherent in existing models, water managers have only a limited set of approaches that can practically and effectively deal with such uncertainties. With respect to downscaling of General Circulation Model (GCM) outputs to the local level, a Regional Climate Model (RCM) is perhaps the most significant current requirement from a hydrological perspective in the climate community. One such practical approach was developed by the International Joint Commission (IJC) for its Lake Ontario-St. Lawrence River study, which looked at revising the Lake Ontario regulation plan and operating rules, as they affected a wide range of uses and public interests. The study (IJC, 2006) used conventional hydrologic approaches to develop and optimize the plans, but also tested their robustness and resiliency under a variety of climate scenarios to see which plan performed best under more extreme conditions.

The information currently available from GCMs is inadequate (and highly variable) for most operational and design aspects of water management decisions. However, there are ways to use the relatively crude information (in terms of the specific needs of hydraulic structural design), under certain circumstances, to improve insights for longer-term watershed planning and vulnerability analysis. Adaptive management is the logical, indirect defensive approach for future oriented planning and operations, and is advocated during the transitional period as improvements in GCMs are made and the information derived from them is more relevant to specific water management decisions.

The problem is that the current suite of GCMs does not provide the basic reliable information that is essential to most of the functions required for decision-making for the various functions of water management (operations, planning, design, regulation and allocation). In fact, for many regions of interest, GCMs do not adequately replicate the historical climate. So there are three basic questions that any water manager must deal with when approaching the issue of climate change under the current constraints of large uncertainties:

(a) What decisions can be made (or be better informed) given the existing limited information from GCMs?

(b) What decisions cannot be made given the limitations and uncertainties of GCM outputs?

(c) How do we account for the significant variations in scenarios from the GCMs?

2. Water sector decision-making

Although hydro-climatologic information about frequencies, magnitude, duration and incidence of precipitation and runoff events are the basic inputs into most water management decisions, they are but precursors to more fundamental economic, environmental and socio-economic information and objectives that typically dominate most water management decisions. In fact, it is the non-hydrologic information that directs and constrains the basic decision rules that societies use to choose from among a wide range of options that can be employed for any given water management problem. Land-use regulations, economic priorities, trade policies, benefit-cost criteria and even the choice of a discount rate in deciding the future value of a stream of benefits and costs derived from a project, are more prominent as decision factors than most hydrologic information. Basic design standards, such as the 100-year (1 per cent) flood, which is commonly used for flood insurance rates, are determined by societal needs.

It is the extremes of weather and climate that are at the core of any water management decision-making. The extremes of water availability – droughts and floods – have major impacts on people's economic, social and environmental circumstances and define the manner in which societies have chosen to adapt to the historical climate. Strategies have been developed for use in water resources management to deal with periods of high demand and low water availability. To do this, the water professionals have access to a historical climate information base that provides climate data in the form of long time series of data, climate norms and statistics, climate extremes and their probabilities.

The traditional flood frequency analysis employs a paradigm of climate stationarity. Statistical analysis necessarily assumes that the array of flood information reflects a reliable and representative time sample of random homogeneous events. The annual maximum peak floods are considered to be a sample of random, independent and identically distributed events. It is assumed that climatic trends or cycles are not affecting the distribution of flood flows in an important way. Global warming brings into doubt the assumption of climate stationarity, since future climate may be different than the recent past.

There are essentially five ways that water managers have of adapting to contemporary climate variability, and which ultimately will serve as the foundation to adapting to climate change:

(a) Planning for new investments or for capacity expansion (reservoirs, irrigation systems, levees, water supply, wastewater treatment, ecosystem restoration);

(b) Operation, monitoring and regulation of existing systems to accommodate new uses or conditions (ecology, climate change or population growth, for example);

(c) Maintenance and major rehabilitation of existing systems (dams, barrages, irrigation systems, canals, pumps, wetlands, among others);

(d) Modifications in processes and demands (water conservation, pricing, regulation, legislation, payments for ecosystem services, consumer education and awareness) for existing systems and water users;

(e) Introducing new efficient technologies (desalting, biotechnology, drip irrigation, wastewater reuse, recycling, solar energy).

2.1 Surveillance, monitoring and assessment

Water management professionals make use of rainfall and streamflow monitoring systems, combined with hydrological models to observe, forecast and warn about flood events. Increasingly, they make use of radars and satellites for rainfall estimation and prediction capabilities to increase both the lead time and accuracy of flood forecasts. This approach uses real-time rainfall, streamflow and water level monitoring to assess and manage the current levels of water supply availability. The amount of real-time information available varies between developed and developing nations with the least developed countries having less such information available.

Increasingly, global weather and climate monitoring systems provide global and regional pictures of current conditions. Without ground truth information, however, such estimates are highly uncertain and of limited benefit apart from raising awareness. This is especially the case with respect to small scale, local variations.

The assessment methodology entails modelling the regional, national or river basin water balance. Many river basins of the world have been modelled and analysed, at least with respect to basic water balance information such as precipitation, runoff, water availability, withdrawals, consumptive losses and groundwater. These will have to undergo another, more detailed round of analysis under assumptions of climate change to determine how robust the existing systems are to the changes associated with various climate change scenarios. However, there are many river basins, particularly in the developing countries and of a transboundary character where water resources assessment is yet to be undertaken systematically.

The information collected through water resources monitoring systems will also be essential in terms of monitoring the impacts (successes and failures) of strategies adopted to adapt to climate change.

2.2 Decision Support Systems: uncertainty and extremes

Numerous variations of Decision Support System (DSS) tools have been developed by the water sector to assist in policy formulation, design, planning and operation of water infrastructure. There is a wealth of information that is being conveyed and applied through numerous mechanisms including international lending agencies such as the World Bank and Asian Development Bank. The water-based agencies of the United Nations, working together under UN-Water, the United Nations coordination mechanism on water issues, are also involved. These agencies include the United Nations Development Programme (UNDP), the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO) and the United Nations Educational, Scientific and Cultural Organization (UNESCO). The UN-Water project collaborates with local partners including the academic, scientific and ministerial arms of developed and developing nations.

There are non-governmental organizations (NGOs) with Websites cataloguing many of these tools and DSSs; the organizations include the Global Water Partnership (GWP) and the International Network of Basin Organizations (INBO). However, these methods are all predicated on a stationary climate hypothesis. Still, these tools and techniques are the foundations for the next generation of DSSs, which can be adapted to the information that is derived from the next generation of GCMs. In addition, many of the new approaches advocate Integrated Water Resources Management (IWRM) as the platform for the next generation of water resources management approaches that are designed to improve the efficiency and effectiveness of water management policies, water resources availability, performance of infrastructure and delivery of services.

The water managers tend to adopt a risk-based management approach in dealing with uncertainty and extremes. Frequency distributions are fitted to extreme datasets and confidence limits used to establish the uncertainty of the magnitude and the probability. For water supply systems, stochastic hydrology techniques and scenario analyses are used to determine water availability. In most instances allocations are based on worst case scenarios, unless there is confidence in climate-related water availability predictions (which currently is not usually the case).

From a technological and engineering standpoint, water managers have routinely dealt with the uncertainties and vagaries of historical climate variability fairly well, but have had much greater difficulties with the institutional and policy aspects of water management, particularly in developing countries. Water availability and vulnerability to natural hazards and uncertainties is more of an institutional failure than one of engineering design or coping with hydrologic uncertainty.

Water managers are used to dealing with risks, hydrologic uncertainties and competing demands. They can build new infrastructure, upgrade and rehabilitate existing infrastructure, reduce vulnerability and increase resiliency and robustness. In fact, one of the standard engineering practices was to account for the uncertainties by designing redundancy to account for them. Hence, levee freeboard was added onto a standard project flood to accommodate the uncertainties involved in designing levee systems. This was the equivalent of applying an early version of the precautionary principle to deal with the unknowns – those aspects of hydrologic phenomena that went beyond conventional risk and uncertainty analysis.

There is a great body of literature on classical risk and uncertainty analysis, and many techniques have been routinely employed in conventional water resources decision-making. The result of employing various permutations of risk, reliability and uncertainty analysis, however, is that the uncertainties associated with climate change are so profound that much of the analysis falls in the realm of mostly qualitative scenario analysis, postulating various permutations of ”what if?” analyses.

Methods routinely used by many water management agencies (such as the United States Army Corps of Engineers) deal with risk and uncertainty of existing hydrologic data, and could be extended, somewhat, in dealing with climate uncertainties (Figure 1). Different types of frequency distributions can be used, using Monte Carlo simulation techniques, to determine how the uncertainties of extreme events affect the economic viability and the technical feasibility of alternative designs – the equivalent of a robustness and reliability analysis [2]. The Corps of Engineers procedures and methods can be combined to estimate the uncertainty in flood damage reduction benefits of a project and, to a certain extent, can be used to analyse the uncertainties associated with climate change. The analysis tests various assumptions through the use of different distributions, including fat-tailed ones that may be more suitable to dealing with the problem of low probability–high consequence impacts, especially in the damage frequency part of the analysis.

The water restrictions and reduced allocations are also used to manage the resources in times of reduced water availability. Restrictions and regulations are applied at key trigger points in water supply availability, usually based on historical information, average inflow predictions and an estimate of the available supply and how long it may last. Restrictions can be applied at various levels and are highly political in their application.

2.3 Socio-economic factors that affect decision-making

The future effects of climate change on water resources in all parts of the world will depend on trends in both climatic and non-climatic factors. Evaluating these impacts is challenging because water availability, quality and streamflow are sensitive to changes in temperature and precipitation. Other important factors include increased demand for water caused by population growth, changes in the economy, development of new technologies, changes in watershed characteristics and water management decisions. There is also increasing recognition of the role ecosystem services can play in water resources management and the importance of coupled social and ecological systems cannot be overlooked.

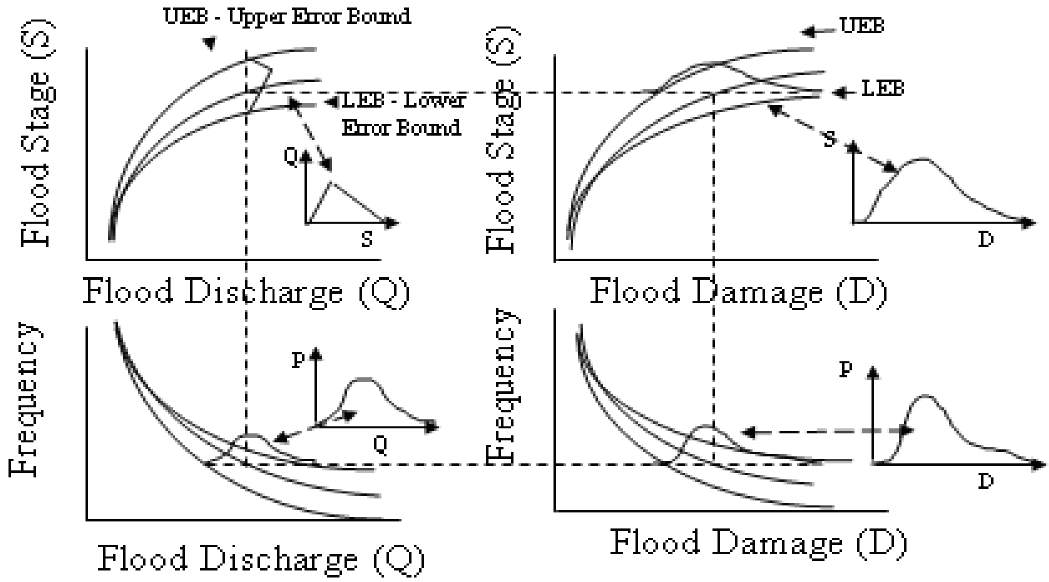

Figure 1. Standard methods for calculating the impact of uncertainty on flood damage calculations (Source: United States Army Corps of Engineers [3])

The choices of specific coping measures together with a long-range strategy depends on the culture of decision-making, specific problems, societal management objectives and the relative scarcity of available resources (natural, human and financial capital), along with the relative susceptibility and vulnerability to natural hazard threats. Governments and water managers must first deal with the identified foreseeable needs of contemporary society as an initial stage before they can move on to preparing for the more uncertain demands associated with climate change (that is, mainstreaming of adaptation measures into management decisions).

Society and the engineering profession, through an historical accumulation of experience, laws, engineering practices and regulations, have defined a narrower acceptable range of expected events to which to adapt. Thus, in some countries we have the 100-year flood plain for flood insurance purposes; we design our urban drainage systems for smaller but more frequent events; and we ensure dam safety by designing spillways for very low-probability floods, roughly of a 10 000 year return period or for the probable maximum precipitation. These are societal judgments made on the basis of many factors, including affordability, relative population vulnerability, and national and regional economic benefits. They are not deterministic criteria made on the basis of empirical or simulation modelling. Defining social risk tolerance and service reliability is part of a social contract to be determined through the political process coupled with public participation – a continuing dialogue within society. But there is no straightforward or acceptable way of transferring flood frequencies from current GCM precipitation data.

As far as specific management measures are concerned, as a general rule, reservoirs provide the most robust, resilient and reliable mechanism for managing water under a variety of conditions and uncertainties. Other combinations of non-structural measures (conservation, pricing, regulation and relocation, for example) may provide comparable outcomes in terms of gross quantities of water supply, but not necessarily in terms of system reliability. The choice of alternatives depends on the degree of social risk tolerance and perception of scarcity as well as economic viability and the complexity of the problem. The permutations for coping with the uncertainties of climate change and variability are limitless – both in the number of strategies and in the combinations of management measures that comprise a strategy. There is no single best strategy – each depends on the factors listed above.

2.4 Stakeholders and mechanisms for interaction

The stakeholders in water resources management are many and varied. They include the National Meteorological and Hydrological Services (NMHSs); water supply managers; irrigators; farmers; hydro-power generators; national, state and local government groups; the general public and many others. Therefore, the mechanisms for involvement and interactions also vary significantly, from high-level Ministerial councils to local meetings and media-based awareness raising and information distribution. Whatever form it takes, the communication of information is a key success factor in water resources management and all mechanisms have a place and provide a benefit.

Another critical aspect of the success of adaptive management strategies is social acceptability of the changes that will be introduced as part of the incremental and essentially experimental programmes that comprise this approach. Informed, consensus-based decision-making and public participation are at the heart of introducing changes to the status quo. Stakeholder involvement is essential in these planning processes and a well thought out and continuous process of facilitated negotiations and conflict resolution among competing interest groups is crucial to the changes that are anticipated in response to climate change.

2.5 Water governance

Water resources management, which has evolved with its core principles of adaptive management – adapting to the risk and uncertainty of considerable climate variability – has employed a variety of tools, in different combinations, to reduce vulnerability, enhance system resiliency and robustness and provide reliable delivery of water-related services. These tools consist of many technological innovations; engineering design changes; multi-objective watershed planning; public participation; and regulatory, financial and policy incentives. However, well-functioning institutions are needed to effectively administer this broad array of fairly complex, dispersed and expensive combination of management measures. Integrated Water Resources Management is the management framework for achieving sustainable development. Governance and IWRM are the principal means for resolving competition among multi-sectoral demands on a fixed water resources base. Each sector (environment, water supply, sanitation, agriculture, hydropower and navigation/transportation) fashions its own set of management principles, rules and incentives that are maximized, often in conflict with one another. Tackling the central issue of governance is a key aspect of any strategy that intends to deal with climate change adaptation.

One of the newest emphases for water management has been institutional reform in how water is allocated, regulated and directed towards the most economic uses via economic incentives. The basis for most modern reforms in water management reside not in engineering hydrology, but in new laws, regulations, national water policies, organizational reforms and economic and financial instruments that promote more efficient water use. These institutional changes are at the core of most World Bank and United States Agency for International Development (USAID) programmes in developing nations, and comprise a key part of IWRM. River basin organizations and watershed planning are the instrumental mechanisms through which most of these non-hydrologic water management reforms are implemented, and constitute the essence of governance.

3. Potential adaptation strategies

Adaptation to current climate variability and potential climate change is a prerequisite for sustainable development and poverty reduction and needs to be integrated into the broader water resources development and management processes. Adaptive management and the precautionary principle, as practiced by water managers, are key concepts that are central to the management of the vast network of existing water infrastructure, including ecosystem infrastructure. The same principles hold for the large proportion of water management demands subject to rainfed agriculture.

There is little difference, if any, in the strategies and techniques one would apply for dealing with climate change versus contemporary climate variability. The big and intractable difference is the much increased degree of uncertainty when dealing with climate change, uncertainty that requires implementing certain strategies that incorporate more redundancy into connected systems, thereby increasing reliability and robustness. The large unknowns, as far as the protection of aquatic species and habitats are concerned, are whether some of these valuable habitats can be sustained during future climate-related hydrologic changes.

There are two dimensions to adaptation – those numerous shorter-term changes that can be implemented readily as part of an ongoing adaptive management approach (monitoring and adjusting operations, for example), and that will serve to increase the resiliency and robustness of existing water management systems, and those fundamental longer-term design changes that are needed to accommodate highly uncertain future climate scenarios for new hydraulic infrastructure.

3.1 Adaptive management

Adaptive management is a decision process that “promotes flexible decision-making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood” [4]. Adaptation to climate change is the encompassing paradigm, and includes adaptive management, which is a continuous process of adjustment and flexible adaptation that attempts to deal with the increasingly rapid changes in our societies, economies and technological changes [5].

Adaptive management is the shorter-term subset of adaptation, which in general, has a longer time horizon. There are numerous adaptive management functions that can be carried out relatively easily using conventional methods that would be associated with operational changes in the existing water infrastructure, coupled with changes in demands and processes for water service delivery. The emphasis should be on those functions that are dependent on a sound knowledge of flood and drought frequencies. Highly uncertain climate change scenarios that form the basis for changes in hydraulic and hydrologic design criteria, and that are needed for planning new long-lived hydraulic structures will require a fundamentally new approach to adaptation, an approach that requires a substantial investment in research and collaboration among the principal practitioners around the globe.

Adaptive management is perfectly suited to many of the immediate efforts needed for operational adjustments in the current infrastructure, for changes in processes and demands, and for maintenance and rehabilitation of existing infrastructure, particularly for irrigation systems and flood risk management in the flood plains of river basins. These are the two water management sectors that would provide the largest and most immediate payoffs in climate change adaptation by reducing the vulnerabilities of existing systems; improving food security, productivity and water use efficiency; and reducing flood damage losses.

For adaptive management to be successful, however, a necessary prerequisite is better and more accessible information through a well positioned monitoring network collecting the requisite information to track the incremental changes that are implemented, and testing their viability and performance so that the necessary adjustments can be made in a timely manner. The establishment of new flood plain zones that are coupled with flood insurance or crop insurance schemes, levee certification, and new operating rules for reservoirs during flood periods are just some examples of modular or incremental adaptation that would be enhanced by a monitoring network and information feedback.

Regardless of the criteria used to determine the best choices (economic efficiency, risk reduction, robustness, resiliency or reliability), an emerging technology has the potential to improve virtually all forms of water management – short-term, mesoscale weather and hydrologic forecasting for 15-, 30- and 90-day periods. Substantial advances are being made in applying this technology in the United States. More reliable short-term weather forecasting for water management purposes represents a key example of how scientific breakthroughs can aid real-time water management and operations, which in turn improve the overall responses to climate variability and greatly increase the efficiency of water management and use, especially for irrigation – by far the largest user of water globally. Also, rapid breakthroughs in biotechnology are anticipated, greatly increasing crop yields while reducing water use. This has great potential in water-stressed areas, rainfed regions and in areas of brackish water. The combination of just these two imminent technological breakthroughs – forecasting and biotechnology – would play a major role in aiding societal adaptation to climate change around the world, especially in developing nations that are most prone to current climate variability.

Strategies have been developed and continue to evolve to address these issues. Implementation of adaptation measures, such as water conservation, use of markets to allocate water, and the application of appropriate management practices will have an important role to play in determining the impacts of climate change on water resources. Adequate tools are not available to facilitate the appraisal of adaptation and mitigation options across multiple water-dependent sectors, including the adoption of water-efficient technologies and practices. In the absence of reliable projections of future changes in hydrological variables, adaptation processes and methods which can be usefully implemented in the absence of accurate projections, such as improved water use efficiency and water demand management, offer no-regrets options to cope with climate change.

3.2 The precautionary principle and water resources management

The Rio Declaration on Environment and Development defined the precautionary principle as follows:

> Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation [6]

The precautionary principle should be applied when a serious risk exists and there is uncertainty about the probability of occurrence but the consequences of the risk are catastrophic. Water resources managers have used a version of the precautionary principle for years. Dam designers must decide how much protection a dam should provide. “The objective should be to balance the benefits of making dams safer against the costs of increased safety and to reduce the risks to acceptable proportions” [7]. The engineering design should consider economic efficiency, to maximize project benefits over costs, and equity to seek a balance between the competing interests of those who benefit from the dam and those who would be harmed by a dam failure. Where a dam failure would cause catastrophic damage and loss of life, designers build the dam to withstand a Probable Maximum Flood (PMF). The PMF “is the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the region” [3]. Economic efficiency is not the primary consideration in the selection of the PMF for dam and spillway design. It is problematic to estimate the probability of a PMF, as the PMF is used to minimize the possibility of a catastrophic failure and loss of life. Hence, it is a traditional example of the precautionary principle applied as part of normal dam safety practice.

Another example of the use of the precautionary principle by water managers is the protection of endangered species. Most agencies are required to conduct their operations so that any action “is not likely to jeopardize the continued existence of any endangered species or threatened species or result in the destruction or adverse modification of habitat of such species” [8]. For example, the operations of reservoirs are required to ensure that the habitat of endangered species is not jeopardized.

3.3 Integrated Water Resources Management (IWRM)

Integrated Water Resources Management provides the institutional basis upon which climate change adaptation can be sustained through the coordination of numerous adaptive management strategies in water-related sectors. The ideal IWRM framework advocates the following essential components/prerequisites:

(a) A national water management plan and/or river basin management plan;

(b) A national water policy/water code;

(c) The harmonization of the policies, regulations and decisions at all levels of government;

(d) The institutional infrastructure that can make consistent decisions and assure progress, manage and monitor resources and effectively deliver services;

(e) The establishment of river basin management authorities.

The essential purpose of IWRM is to manage water more efficiently and effectively. Integrated Water Resources Management requires the harmonization of policies, institutions, regulatory frameworks, planning, operations, maintenance and design standards of the numerous agencies and departments responsible for one or more aspects of water and related natural resources management. Water management can work effectively (but not necessarily efficiently) in fragmented institutional systems (for example, the federally based systems of the United States, Brazil and Australia), where there is a high degree of decision-making transparency, public participation and adequate financial support for planning and implementation. Water management does not work well in most other cases where these prerequisites do not exist. Setting up the proper institutional framework is the first, essential step towards IWRM, especially if climate change is likely to increase resource scarcity and stresses on natural systems. A well functioning institutional system will be the foundation on which climate adaptation can be implemented effectively.

There has been but partial success in the past in embracing the integrated approach to Water Resources Management. Although concepts and processes are robust, well understood and widely known, their assimilation into the decision-making processes has progressed rather slowly. Climate change has brought increased appreciation for multi-sectoral and multidisciplinary collaborative efforts towards sustainable development. This cultural change should be seized as an opportunity.

3.4 Vulnerability assessment

Vulnerability assessments and risk management are critical to sound adaptation strategies. It is important to understand the impacts on the water cycle, and the consequent effects on ecosystems, people and economies. Hydrologic runoff sensitivity to climate change may be differentiated from water management vulnerability and societal susceptibility to economic disruptions and dislocation resulting from climate change. Hashimoto et al. [9] introduced taxonomy to account for risk and uncertainty inherent in water resources system performance evaluation. The five terms listed below simply represent a set of descriptors that characterize and extend the key components of more traditional engineering reliability analysis, that is, they focus on the sensitivity of parameters and decision variables to considerations of uncertainty, including some aspects of strategic uncertainty. These terms are:

(a) Reliability – a measure of how often a system is likely to fail;

(b) Robustness – the economic performance of a system under a range of uncertain conditions;

(c) Resiliency – how quickly a system recovers from failure under extreme conditions (floods, droughts);

(d) Vulnerability – how severe the consequences of failure may be;

(e) Brittleness – the inability of optimal solutions to accommodate unforeseen circumstances related to an uncertain future.

The relative vulnerability of a water resources system, then, is a function of hydrologic sensitivity (as input to the managed system) and the relative performance (robustness) of a water management system as it affects the delivery of services required by society. This is more of a technically defined management function that can be quantified according to various scenarios of climate change. Societal susceptibility to climate change, on the other hand, depends on numerous factors outside the control of water managers, such as land use regulations, proper allocation of water supplies and population growth and economic policies related to water uses. Without an integrated water management capability, society becomes increasingly susceptible both to population-driven increases in water demands, as well as climate change variability. In other words, susceptibility and vulnerability increases not so much because of increased hydrologic variability, but more as a function of an inadequate institutional infrastructure required to manage those resources.

In many cases, upgrading the institutional capacity of developing nations to implement sound water management practices is the most effective way of reducing vulnerability due to climate change. The following questions can guide the process:

(a) Who has the authority and responsibility for the existing statutes, policies and regulations for dealing with extremes and contingencies?

(b) Who is responsible for climate adaptation planning?

(c) Who operates and maintains existing water infrastructure? Is it at capacity? Can it serve projected needs? What is needed over next 10–20 years?

(d) What does the future look like under various socio-economic scenarios of growth and development? How will future demands for resources be met? What is role of water?

(e) What is the vulnerability to current climate variability – floods and droughts? How will this change under future climate scenarios and growth in 2050?

3.5 Emergency preparedness and response

Political will and substantial financial resources are needed to catalyse the actual implementation of the series of preparatory measures, strategies and plans that need to be developed. But one must be prepared for the next big event, whether it is a devastating drought, flood, typhoon or hurricane. The emergency preparedness and response function is both the leading edge and core of proactive climate adaptation. Every dam, levee system, water supply system and irrigation system needs to have an emergency response plan to deal with events that are beyond the design criteria (spillway flood, dam failure or levee overtopping) or firm yield of the system. Every unforeseen or catastrophic event is an opportunity for reform and implementation of adaptive solutions and strategies. Water managers must lead the way and become more proactive in promoting the basic elements of adaptive management that are under their control, and that are inherently technical in nature. That is the essential starting point for adaptation.

Emergency response, particularly during the initial stages, requires strongly motivated and competent technical professionals to ensure that the support provided is efficient, cost-effective and sustainable. Therefore, preparatory measures should invariably include capacity-building programmes to develop a pool of technically capable emergency response staff in disaster prone regions, and establishment of a predictable capability to aid deployment of these staff in the shortest possible time.

3.6 Cooperation in transboundary river basins

Where appropriate, cooperation in transboundary river basins is both necessary and beneficial in adapting to climate change. It is not only necessary to ensure that unilaterally taken measures do not have substantial negative effects in neighbouring countries, but can also bring mutual benefit for all riparian parties, for example by sharing costs and benefits of adaptation measures or by reducing uncertainty through exchange of data and information. Cooperation in transboundary river basins is needed at all steps of impact assessment and the development of an adaptation strategy. Usually, the river basin scale is the appropriate scale for impact assessment and developing adaptation measures. Joint monitoring or at least data sharing and elaboration of common scenarios in neighbouring countries is needed to facilitate agreement on expected impacts of climate change. Cooperation is also necessary in vulnerability assessment and during the development of adaptation measures.

3.7 Technological advances

One of the obvious investments in technological development that is expected to have immediate payback is improved forecasting and prediction techniques that will undoubtedly improve operation and management of existing water delivery systems, and open up possibilities for the trading of water rights and other risk-sharing programmes. But forecasting requires much more investment in scientific research, as well as installing and maintaining hydro-climatic monitoring systems in each river basin. Recent advances in genetic engineering and biotechnology are expected to have the greatest impact on food security and agriculture, alleviating some of the stresses on fresh water supply, as the vast reservoirs of brackish groundwater might be used for certain forage crops. Advances in fusion energy and cheaper solar power would alleviate water supply problems for the large urban areas on the coasts, making desalination an economically competitive option. Cheaper solar energy would do the same for small villages and remote rural areas, making subsistence much easier by making available groundwater sources for water supply and small-farm irrigation water for livestock, while reducing the costs of water treatment and sanitation.

Further technological and other advances could also include aspects of drought resistance, drought avoidance and reduced transpiration, as well increased tolerance of crops to saline water. Low cost biotreatment regimes for urban wastewater and appropriate micro-irrigation technology also offer significant improved water resources management capabilities in developing countries.

These technological advances are essential for climate change adaptation, yet do not require complex institutional systems for implementation, that is, they can be implemented without a fully organized IWRM strategy or institutional infrastructure.

4. Needs for tailored climate products and services

4.1 Direct and indirect impacts of climate on the water sector

There are a range of direct and indirect impacts of climate on the water resources availability and demand. In most instances a decrease in rainfall results in an even greater decrease in river runoff/streamflow and inflows to groundwater storages. The dry conditions mean that greater rainfall is necessary to replace soil moisture, and vegetation in dry times can impact on river runoff. Increases in evaporation can have a direct impact on the losses from major storages and river systems. Increased rainfall intensity can also lead to increases in runoff as soil moisture stores are full and a greater percentage of the rainfall runs off.

In dry periods, the demand for water from most users increases with the urban sector seeking supplies for lawns and gardens and the agriculture sector seeking supplies for crops and pastures. Conversely, in wetter times there is less demand on water supplies and supply systems can be refreshed, including, for example, groundwater resources. Extreme dry climate conditions can impact on vegetation through both changes in the vegetative cover and destruction of the vegetative cover (bushfires). Both of these factors can mean that once the dry conditions abate additional rainfalls above average amounts are required before significant runoff can occur.

The combination of increasing rainfall extremes and degraded vegetation coverage also has the ability to increase the likelihood of flash floods, ice jams and landslides. All of these can also impact on the ecological balance of the water system and thus have major implications for water quality (algal blooms, for example).

4.2 Climate information needs

There are many levels of decision-making typically involved in water management – from the national policy level down to the individual household and farmer. Each user has specific requirements for climate information to factor in their decision-making processes. A farmer needs climatological information and short-term forecasts to decide which crops to plant, when to sow and when to harvest. A farmer or irrigation district manager needs seasonal forecasts to optimize the allocation and use of water, often in conjunction with groundwater withdrawals and rainfall. The individual users typically have shorter time horizons than the managers or politicians. The policymakers have the longest time horizons in deciding allocation rules, water use priorities during droughts, regulations guiding water quality and entitlements to various water-using sectors, as well as economic development policies which depend on water availability (the production of farm-based ethanol, for example).

Table 1 below is a starting point for identifying the needs for meteorological (climate and weather) data in addressing the various fields of application of hydrological analysis. As we move from specific hydrological applications to more detailed social, economic and environmental adaptation mechanisms, we will need to expand the characteristics and types of climate information required.

To understand the requirements of climate products and services for water management, one only needs to look at the trends in the analysis of climate information in support of hydrological and water resources activities. Hydrological analyses have evolved from the basic start of the Rational Formula through various statistical analyses involving the estimation of extremes of flow and low flow through to complex hydrological models of the water balance and hydrological parameters and the emerging global/regional earth systems modelling.

Table 1. Basic meteorological information needs of the hydrological sector

Field of application	*Hydrological element needed*	*Meteorological element needed*	*Type of meteorological input data*	
			Timescale	*Space Scale*
Data processing, plausibility check of hydrological data	Runoff	Precipitation	d, m	s, a
Water balance (non real-time)	Runoff Evaporation Soil moisture Groundwater	Precipitation Radiation Sunshine duration[1] Air temperature [1] Air humidity [1] Wind speed [1]	y, m, d d, m d, m d, m d, m d, m	a s, g s, g s, g s, g s, g
Simulation of time series (non real-time)	Runoff Groundwater Water temperature Dissolved matter [2]	Precipitation Radiation Air temperature Air humidity	y, m, d d, m h, d, m	a s, g s, g
Extreme value statistics of floods and low flows (non real-time)	Runoff Water level	Precipitation	y, m min, max	s
Forecasting (real-time)	Runoff Water level Snow cover Water equivalent of snow Snow melt Soil Moisture	Precipitation Radiation Air temperature	h, d d h, d h, d	s, a s, a s s

s = point values a = areal values g = grid values
y = annual values m = monthly values d = daily values
h = hourly values min = minimum values max = maximum values

1 = meteorological elements needed for the calculation of evaporation
2 = averages of selected weather stations (dry and wet weather conditions)

The recent past has seen greater cooperation and collaboration between the water and the climate communities. A challenge for the future is for the climate community and the hydrological community to work together to span the temporal and spatial divide created by the different modelling platforms that have evolved. A process for identification of requirements can be defined as follows:

(a) An assessment of the impacts of climate on a set of different types of projects and plans;

(b) The development of methods, standards and procedural guidelines for impact assessment and climate adaptation;

(c) The production of guidelines for integrating impact assessments into planning at the local level;

(d) The establishing and promoting of recommendations for legal requirements for climate adaptation.

Both the climate and the hydrological perspectives are important. Hydrologists need to have climate services and products targeted to the requirements for their modelling practices. This means having climate information with the format and characteristics that can be accepted by the hydrologists' models. Hydrologists also need to work closely with the climate (and weather) communities to see the extent to which the climate modelling paradigm can be applied to provide the water sector with decision-making tools and advice.

Many of the methods for incorporating climate information into water management, however, are still experimental. Climatologists, for example, provide forecasts of precipitation and temperature with 13 months' lead time. The forecasts generally are for large spatial areas and for three months at a time. The seasonal outlooks are for temperature and precipitation and are not in a format that is readily useable by water managers. The spatial and temporal scales also are generally not appropriate for water management on the basin or watershed scale. Several methods have been proposed to develop seasonal forecasts of surface water that use climate information. However, new forecasting methods are yet to be fully tested over long time periods and are considered unreliable.

4.3 Operational requirements

From an operational perspective, there are two major requirements from the water managers: climate-related statistical services and products that provide valuable input into the design of hydrological structures; and climate information that enables the operation of these systems on a day-to-day basis. This second requirement relates to the operation of hydrological structures and the supply of water. Water resources are allocated on the basis of current storage levels and potential inflows. Current storage levels are a relatively straightforward matter, but potential inflows are more difficult to predict. Water professionals tend to use the average or worst conditions experienced over historical periods as the best indicator of potential inflows. If the climate is changing, however, then the historical average or worst historical sequence may not be the best indicator of potential inflows, and the operational agency may under- or over-allocate the available water supply.

A further aspect of this water management issue is that of wastage of water through releases (rain rejection). Just prior to a rain event, managers release water required to irrigate crops, and the rainfall effectively replaces the water intended for irrigation. The released water flows through the system without being used and while it is not lost to the environmental system, its use is lost to the sector that was allocated the resource. While this example is closer to weather than climate services, the development of seamless weather and climate services would see improved tools in this regard.

Operational changes are inherently oriented towards improving the use and performance of the existing water resources delivery system for all of its designed and de facto uses. For example, most reservoirs undergo periodic reviews of their operating rules, either as part of new and expanded hydrologic records, or because new uses or purposes are added (recreation, environmental flows or protection of endangered species, for example). These are the opportunities for updating the drought and flood contingency plans based on new information that could improve the overall resiliency, robustness and reliability of the system. These revisions may take into account changes in peak flood periods, snowmelt timing or updating of flood and drought frequency analysis based on new methods and extended data, along with scenarios based on GCMs that would test the robustness of the operating system.

Figure 2 shows the various United States Army Corps of Engineers operating procedures and manuals that are related to reservoir management, and that are routinely revised and adapted as new information becomes available. These operating procedures are prime candidates for updating as part of a comprehensive adaptation strategy on the part of the water management community. The Corps, in fact, will be undertaking a series of stress tests on their reservoir systems to determine how they would perform under a variety of climate scenarios. These tests will form the basis for updating many of the regulations, operating procedures and manuals shown in the figure.

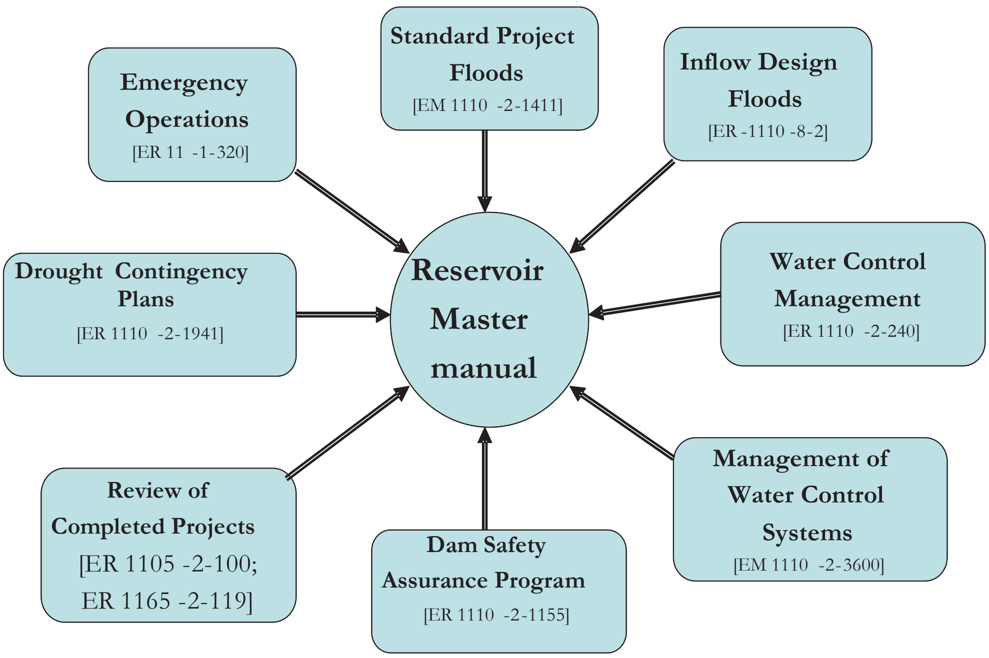

Figure 2. United States Army Corps of Engineers manuals and regulations for reservoir operating procedures

Operational flexibility could be enhanced by introducing new risk-based forecasting methods and decision criteria, such as El Niño forecasts coupled with likely runoff forecasts. Better forecasts can increase water delivery and hydropower production at most reservoirs, but depend on the reliability of the forecasting methods being improved. Conjunctive use of groundwater and surface water as a part of a more sophisticated water management strategy is another operational change that can be implemented now with fairly conventional methods and techniques, associated with an adaptive management plan (monitoring, feedback and adjustment to operating rules).

The water sector has to employ the additional tools of reduced allocations (for the agriculture sector) and water supply restrictions (for urban and rural communities). Both of these tools can be put to better effect if future climate information is available. Advanced knowledge of lower than normal rainfall periods may lead to an early application of restrictions, saving valuable resources for future requirements. For example, in the important area of rainfed agricultural systems, more reliable 30-, 60- and 90-day forecasts would provide significant benefits.

Thus, the water sector has in the main developed its operational activities assuming a stationary climate and its tools and decision-making systems are geared for such input. The requirements of the water sector are therefore for scenarios of future potential climate information along with a probability of occurrence and, where possible, information on the uncertainty of the estimates. The water sector is used to dealing with probabilities and applying a risk-based management approach. The products and services must be targeted to such an approach.

4.4 Planning and adaptation requirements

A key input to hydrological infrastructure studies is information on the frequency of extreme rainfall events. The ranges of interest include high frequency events (say, 1 in 2 to 1 in 10 years) through to extreme, low frequency events such as 1 in 100 years, along with estimates of probable maximum precipitation. In a stationary environment, such estimates can be, and have been, readily derived from statistical and other analyses of historical data, but in a changing world such techniques will lead to incorrect estimates and thus under- or over-design of hydrological structures.

From a planning perspective, the situation is not that much different, except for the timescale. Historically, hydrologists have used climate information to extend historical streamflow data back in time and then analysed this record to determine a safe yield for the system. In recognition that the historical record may not contain the worst drought possible, a risk-based approach has been applied whereby probabilities of available supply have been produced using a variety of techniques including stochastic streamflow generation. As indicated above, climate as well as being a driver of supply is also a driver of demand. In summer months, water demands are higher than in winter months and extreme summers place heavy demands on water supplies for urban, agricultural and hydropower uses.

Based on population and other demand (increasing agriculture) the water sector plans the construction and introduction of new supplies (dams, desalinization plants, water recycling and water reuse, for example) and/or initiates programmes aimed at reducing overall water consumption (such as restrictions) and at raising awareness. Climate as a driver of both supply and demand is a key consideration in the planning of future water supply options. Again, the assumption of a stationary hydrological cycle has been fundamental to the decision management approaches adopted in the past. If as seems to be certain we are not facing a stationary cycle, we must begin to incorporate possible future conditions into our planning and adaptation approaches. This may well include a variety of different measures as described above, but applied in a stronger and more effective risk-based management approach.

The water sector must position itself to accept an ensemble approach to climate products and services and provide probabilistic approaches to water supply planning. However, to do this, the climate community must be able to provide future climate ensembles at the temporal and spatial scales necessary for incorporation into the current hydrological modelling approaches. Alternatively, the hydrological community could also look at its modelling approaches and seek to have them more closely aligned with climate modelling capabilities. A partnership approach is necessary.

The importance of obtaining and analysing long-term observations of the hydrological regimes of river basins not affected by human activity (low levels of regulation and land-use changes) for monitoring the impacts of climate change on the hydrological regimes cannot be over-emphasized.

4.5 Product and service characteristics

The table in Section 4.2 identifies the temporal and spatial requirements for climate information for hydrological purposes. These are not necessarily the characteristics of climate information that come from the global and regional climate modelling approaches. Rainfall is highly variable across a catchment and hydrological models are not geared to accepting grid-based, averaged rainfalls. Therefore, it is essential that attempts are made to both develop and implement downscaling approaches that provide the required climatological inputs into hydrological models, and at the same time to continue to develop hydrological components of global and regional climate models. The issue with the latter approach is that the water sector would have to develop a wide range of tools that feed off the climate-hydrological modelling interface and provide the right types of information, products and services on which the water professional could act. This may take a significant change in both the skill set and culture of the water sector.

Product and service characteristics (requirements) will vary from situation to situation. For example, in systems that rely heavily on snow-fed water supplies, changes to snow depth and snowmelt rates may impact on the availability, access to and use of water in those regions.

4.6 Dissemination and communication aspects

It is fair to say that until recently the climate and water communities have acted in relative isolation of one and other. There has been closer collaboration between the weather and climate communities and hence the movement towards global climate modelling. Advances in climate monitoring, modelling and prediction have not resulted in similar advances in these capabilities within the water sector.

The climate sector must improve the communication and delivery of climate-related information, accompanied by documentation on its quality and accuracy, to ensure that the various user sectors can make informed decisions on its use. The hydrological community should also look closely at its approaches and techniques to see if they can be better tailored to accept the products/outputs from the climate sector.

The more the hydrological and water communities can work together to provide joint updates and joint delivery of services, the greater their creditability and the appreciation of the general public will be. It is essential that the community is not presented with mixed messages, and that the expectations, uncertainties and suggested actions are consistent.

The primary role of the media will be in keeping the general public informed of what the two sectors have discovered, what it means to them and how these communities will work together into the future to ensure the sustainable use of the valuable water resource.

5. Assessment of gaps and needs

The Intergovernmental Panel on Climate Change [1] states that:

> The ability to quantify future changes in hydrological variables, and their impacts on systems and sectors, is limited by uncertainty at all stages of the assessment process. Uncertainty comes from the range of socio-economic development scenarios, the range of climate model projections for a given scenario, the downscaling of climate effects to local/regional scales, impacts assessments, and feedbacks from adaptation and mitigation activities. Limitations in observations and understanding restrict our current ability to reduce these uncertainties. Decision-making needs to operate in the context of this uncertainty. Robust methods to assess risks based on these uncertainties are at an early stage of development.

5.1 Identification of gaps between products and services available and those required

The IPCC [1] identifies the following major gaps in observations of climate change related to freshwater and hydrological cycles:

(a) Difficulties in the measurement of precipitation remain an area of concern in quantifying global and regional trends. Precipitation measurements over oceans (from satellites) are still in the development phase. There is a need to ensure ongoing satellite monitoring, and the development of reliable statistics for inferred precipitation.

(b) Many hydrometeorological variables such as stream flow, soil moisture and actual evapotranspiration, are inadequately measured. Potential evapotranspiration is generally calculated from parameters such as solar radiation, relative humidity and wind speed. Records are often very short, and available for only a few regions, impeding complete analysis of changes in droughts.

(c) There may be opportunities for river flow data rescue in some regions. Where no observations are available, the establishment of new observing networks should be considered.

(d) Groundwater is not well monitored, and the processes of groundwater depletion and recharge are not well modelled in many regions.

(e) Monitoring data are needed on water quality, water use and sediment transport.

(f) Snow, ice and frozen ground inventories are incomplete. Monitoring of changes is unevenly distributed in both space and time. There is a general lack of data from the Southern Hemisphere.

(g) More information is needed on plant evapotranspiration responses to the combined effects of rising atmospheric CO_2, rising temperature and rising atmospheric water vapour concentration.

(h) Quality assurance, homogenization of datasets, and inter-calibration of methods and procedures could be important whenever different agencies or countries maintain monitoring within one region or catchment.

5.2 Research and technology requirements

The IPCC [1] identifies the major uncertainties in understanding and modelling changes in climate relating to the hydrological cycle as including the following:

(a) Changes in a number of radiative drivers of climate are not fully quantified and understood (including aerosols and their effects on cloud properties, methane, ozone, stratospheric water vapour, land-use change and past solar variations).

(b) Confidence in attributing some observed climate change phenomena to anthropogenic or natural processes is limited by uncertainties in radiative forcing, as well as by uncertainty in processes and observations. Attribution becomes more difficult at smaller spatial and temporal scales, and there is less confidence in understanding precipitation changes than there is for temperature. There are very few attribution studies for changes in extreme events.

(c) Uncertainty in modelling some modes of climate variability, and of the distribution of precipitation between heavy and light events, remains large. In many regions, projections of changes in mean precipitation also vary widely between models, even in the sign of the change. It is necessary to improve understanding of the sources of uncertainty.

(d) In many regions where fine spatial scales in climate are generated by topography, there is insufficient information on how climate change will be expressed at these scales.

(e) Climate models remain limited by the spatial resolution and ensemble size that can be achieved with present computer resources, by the need to include some additional processes and by large uncertainties in the modelling of certain feedbacks (from clouds and the carbon cycle, for example).

(f) Limited knowledge of ice sheet and ice shelf processes leads to unquantifiable uncertainties in projections of future ice sheet mass balance, leading in turn to uncertainty in sea-level rise projections.

With respect to the climate–water interface, the IPCC [1] identifies the following gaps and research needs:

(a) Further work on detection and attribution of present-day hydrological changes is required, in particular, changes in water resources and in the occurrence of extreme events.

(b) There remains a scale mismatch between the large-scale climatic models and the catchment scale – the most important scale for water management. Higher resolution climate models, with better land surface properties and interactions, are therefore necessary to obtain information of more relevance to water management. Statistical and physical downscaling can contribute.

(c) Most of the impact studies of climate change on water stress in countries assess demand and supply on an annual basis. Analysis at the monthly or higher temporal resolution scale is desirable, since changes in seasonal patterns and the probability of extreme events may offset the positive effect of increased availability of water resources.

(d) The impact of climate change on snow, ice and frozen ground as sensitive storage variables in the water cycle is highly non-linear, and more physically and process oriented modelling, as well as specific atmospheric downscaling, is required. There is a lack of detailed knowledge of runoff changes caused by changing glaciers, snow cover, rain–snow transition and frozen ground in different climate regions.

(e) Methods need to be improved to allow the assessment of the impacts of changing climate variability on freshwater resources. In particular, there is a need to develop local-scale datasets and simple climate-linked computerized watershed models that would allow water managers to assess impacts and to evaluate the functioning and resilience of their systems, given the range of uncertainty surrounding future climate projections.

(f) Feedbacks between land use and climate change (including vegetation change and anthropogenic activity such as irrigation and reservoir construction) should be analysed more extensively; for example, by coupled climate and land use modelling.

(g) Climate change impacts on water quality are poorly understood for both developing and developed countries, particularly with respect to the impact of extreme events.

(h) Impacts of climate change on aquatic ecosystems (not only temperatures, but also altered flow regimes, water levels and ice cover) are not understood adequately.

(i) Despite its significance, groundwater has received little attention in climate change impact assessment compared to surface water resources.

5.3 Infrastructure, education, training and other capacity-building requirements

Clearly, in this transition period of moving from a conventional hydrological analytical paradigm to one that attempts to encompass a great deal more uncertainty stemming from climate change, the capacity-building requirements must keep pace with the innovations and technological developments associated with the development of a new analytical paradigm. There is a danger, however, that in this transitional period, too many untested and scientifically questionable methods are being advocated and applied to a variety of water management problems. There has not been enough thought, time, research and effort invested in the development of a new generation of models and methods duly tested and peer-reviewed by water managers and practitioners.

Across all water-related disciplines (especially those where protection of life is a major concern) consideration should be given to ensuring that technical staff meet a defined set of special competencies. The competencies should be developed and nurtured through experience and targeted training activities, combined with an evaluation and accreditation system. It is essential that competent and well trained technical and professional officers provide the basis for informed water resources management decisions.

A major contribution to improved management of water resources will flow from the development of geospatial representations of the geographical and other factors that influence the flow and connectedness of water resources (the geofabric). This will enable improved mapping of cause–effect relationships and ensure that double counting is minimized and water balances are geographically and spatially sound.

The reality, however, is that capacity-building and training must run in parallel to the testing and development of various methods and models. It is encouraging to see that such prominent organizations as the World Bank, USAID, WMO, the United States Army Corps of Engineers and the United States Bureau of Reclamation, and many other institutions around the world are involved in various substantive efforts to apply new approaches and train their users simultaneously.

5.4 Methodologies for cost-benefit analyses

The IPCC [1] states that there are relatively few results available on the socio-economic aspects of climate change impacts related to water resources, including climate change impacts on water demand. One comprehensive study, which employed the use of climate scenarios to determine the robustness and resiliency of various plans that were optimized on the 160-year historical record, considered the development of new operating rules for the regulation of Lake Ontario and the St. Lawrence River system for navigation, hydropower, recreational boating, ecology and marsh restoration, water supply and shoreline erosion [10].

Neither the methodology to undertake consistent and comparative cost-benefit analyses of climate change scenarios nor case studies of their application have been adequately developed as yet, principally because most cost-benefit analysis depends on hydrologic frequency analysis as the basis for projecting the future stream of benefits and costs of any management options. The problem for economic analysis of climate change impacts, and associated benefits and costs, is that future uncertainties (based on GCMs) are so large as to negate most conventional economic techniques that are based on flood and drought frequencies, and rely on discount rates to derive a present worth of a future stream of benefits. Cost-benefit analysis, like most hydrologic analysis, is based on expected utility and copes with uncertainty in the form of thin-tailed probability density functions. In fact, under the anticipated growth in climate change uncertainty, both hydrologic events and related economic consequences may well be fat-tailed distributions reflecting low probability, high consequence events. There are no adequate theories and associated methods to effectively deal with a very different and highly uncertain evolution of climate change events. Yet they are essential to the planning, evaluation and design of long-lived infrastructure such as water supply distribution systems, urban storm water drainage systems and other large hydraulic infrastructure such as dams, tunnels, canals and pipelines.

5.5 Relationships between climate sector and water sector

As indicated above, the relationship between the climate and water sectors has not been as strong as it could and should be. The timing is right for a new initiative to bring the climate and water sectors closer together to address key issues associated with the sustainable management of our precious water resources into the future. In a results-based environment, closer cooperation will be required to ensure that the climate sector produces products and services adequate to meet the requirement of the water sector and for the water sector to inform and explain its needs to the climate sector.

In terms of the required climate–water interactions, the potential for the development of extreme hydrological events which can occur in a region should be taken into consideration. In the case of floods arising from various sources (spring, flash floods, floods caused by wind-induced surge, operation of reservoirs or floods associated with tropical cyclones), the climate information for the region, where these phenomena have direct relevance, should contain the climatic data required to assess and manage the situation. In cold regions, climate conditions can determine the occurrence of other extreme hydrological events that may vary substantially under the influence of climate change. For example, there are ice jam events which are governed by the ice breaking processes on rivers and determine channel capacity in spring when the water content of a river and constriction of flows can be high. In each case a different set of climate data is necessary.

In southern regions, low runoff and droughts pose the greatest threat for the community and the economy, and may affect municipal and agricultural water supplies, and impede power generation and water transportation. This problem becomes a political one for the countries within transboundary watersheds where droughts and lack of water occur regularly and may become more frequent under the impact of climate change.

Therefore, better understanding of the interrelationships between climate and hydrological information requires the development of sets of certain characteristics of climate information for certain hydrological processes and geographical regions where these hydrological processes can bear an extreme and dangerous character.

The major next step in the practical use of climate information in the forecasting of hydrological phenomena, and for application in the water sector as a whole, should be improvement to the existing monitoring systems, taking into account the essential linkages between climate and hydrological parameters.

6. Summary

As the fundamental drivers of the hydrological cycle are affected by increasing climate variability and climate change, they will have large impacts on water resources availability and demand. Water is predicted to be the primary medium through which early climate change impacts will be experienced by various sectors and is expected to affect sustainable development and to jeopardize economic development and poverty reduction efforts. These changes in water availability and demand will exacerbate existing issues in sectors such as health, food production, sustainable energy and biodiversity. Increased water-related risks associated with the changes in frequency of extreme events such as flash floods, storm surge and landslides, will put further stresses on these sectors. It is critical to understand the processes driving these changes, the sequences of the changes and their manifestation at different spatial and temporal scales.

The future challenges to water resources management will, however, depend as much on non-climatic factors such as population growth, urbanization and changes in economic development. Sound water management is built upon long-term hydrological and meteorological monitoring networks that provide robust, accurate, timely and consistent data, and is affected by the social, environmental and economic factors that drive the demand for water use and services, determine technological options, and provide the backdrop to adopted solutions. Water management options have to be considered in consultation with hydro-climatic scientists, water planners, water managers, social scientists and other stakeholders (users and decision-makers in other sectors) to facilitate adaptation under climate variability and/or climate change. The water sector has had partial success in the past in embracing the integrated approach to water resources management. Although the concepts and processes are robust, well understood and widely known, their assimilation into the decision-making processes has progressed rather slowly. Climate change has brought increased appreciation for multi-sectoral and multidisciplinary collaborative efforts towards sustainable development. This cultural change should be seized as an opportunity.

Adaptation to increasing climate variability and climate change in the water sector needs to be guided by following principles:

(a) Broader development context: Adaptation must be addressed and applied in a broader development context, recognizing climate variability and climate change as an added challenge to reducing poverty, hunger, diseases and environmental degradation by truly integrating measures for adaptation to climate change with water resources management plans, physical land planning, infrastructure development, Poverty Reduction Strategy Papers (PRSPs), national development strategies and all other relevant development plans and programmes.

(b) Improving governance: Collaborative governance and the strengthening of institutions for land and water management is crucial for effective adaptations. Suitable institutional mechanisms to enable adaptive management should be build on the principles of participation of civil society, equality, subsidiarity and decentralization. Transparency of all decision-making processes and procedures must be ensured.

(c) Improving and sharing knowledge and information**:** Access to information relevant to policy and management will be fundamental in building capacity to cope with increasing variability and change. Information and knowledge for local adaptation must be improved, and must be considered a public good to be shared at all levels. Increased research and development oriented towards climate change and resulting variability through interagency collaboration for jointly developing tools and procedures and applied research for adapting to climate change should be supported.

(d) Addressing the economic and financial aspects**:** The cost of inaction and the economic and social benefits of adaptation actions call for increased and innovative investment and financing. A paradigm shift is required in the methods that are used for justifying new water resources investments and projects, a shift that includes very different economic decision criteria.

(e) Building resilience: Building resilience to ongoing climate variability and future climate change calls for adaptation to start now by addressing existing problems in land and water management. It should be recognized that most of the adaptation measures taken to adjust to the current variability will also help adapt to the future climate change.

7. Recommendations from the water sector

(a) Water management options to facilitate adaptation to increasing climate variability and climate change should consider changes to operations, demand management and infrastructure. Decision-making frameworks using robust solutions should be encouraged. Adopting alternatives that perform well over a wider range of future scenarios could improve system flexibility. This requires an appreciation of existing and potential uses of water resources.

(b) Because climate change is a creeping, slowly evolving and uncertain phenomenon in a politicized world that has profound difficulties in dealing with uncertainties, it will not serve to catalyse actions that may require huge investments upfront to avoid unknown risks. The following pragmatic, proactive adaptive management approach, comparable to the no-regrets philosophy espoused by many advocates of climate change adaptation, is recommended:

(1) Vulnerability assessment of water infrastructure;

(2) Increased oversight, inspection and regulation of infrastructure during operation and maintenance;

(3) Life cycle management of aging infrastructure;

(4) Development of forecasting methods for implementation of improved soft measures in water management, such as better reservoir and emergency operations;

(5) Strengthening of emergency management and preparedness plans for managing risks associated with extreme events;

(6) Risk-based planning and design of new infrastructure to account for climate uncertainties;

(7) Development of a new generation of risk-based design standards for infrastructure responding to extreme events.

(c) The issues that confront water managers and infrastructure designers require pragmatic approaches and tools – even if they are transitional in nature. It is important that the methodologies developed be derived from existing conventional methods for risk and uncertainty analysis.

(d) No individual water management agency and affiliated research institute can develop the new principles and tools that water managers and design engineers can use effectively to adapt to climate change. An internationally coordinated, collaborative applied research and development effort needs to be undertaken that routinely deals with practical implementation issues for water management. Transition of research to effective operations is a major challenge and it is important that the research institutions engaged in this effort working closely with operating water management agencies.

(e) Climate data and information are essential and provide the foundation upon which adaptation strategies are developed. Such climate information, whether for the short, medium or long term, should be tailored to serve water managers' needs at national, regional and local levels. Water professionals must take the responsibility to specify these information needs.

(f) The state of General Circulation Model projections are such that their regional details are significantly inconsistent with observations, particularly in quantitative values of extreme events, and as such cannot be used as reliable information for water management needs. The focus of climate studies must begin to shift from generic global information to the local, particularly river basin and sub-basin, levels to understand impacts and assessments of more focused adaptation and response options.

(g) There is a lack of detailed knowledge of runoff changes as caused by changing glaciers, snow cover, rain–snow transition and frozen ground in different climate regions. Climatic information on extremes, which can be used for impact assessments at monthly or higher temporal scales, is required since changes in seasonal patterns and the probability of extreme events may offset the positive effect of increased availability of water resources in some regions.

(h) The effects of climate change on water quality, aquatic ecosystems (not only temperatures, but also altered flow regimes, water levels and ice cover) and groundwater are poorly understood, particularly with respect to the impact of extreme events, despite their significance for water resources management. Further research to provide adequate information on them is required. The research on climate and water cycle should be further enhanced.

(i) There is a need to reduce the scientific uncertainties in understanding the impacts of climate change on the availability of water resources. Decision-makers in the water sector need to understand the uncertainties inherent in climate predictions and the trade-offs required between longer-term prediction of climate information at the local or regional scale, and the potential decrease in accuracy or increase in vulnerability.

(j) Climate models cannot replicate droughts and the inherent persistence in those phenomena. Drought early warning is essential, especially for the large regions of rainfed agriculture. Flood and drought preparedness, warning and response planning are the essential elements of adaptive management.

(k) Floods serve as an important water resource and enhance various environmental services. They need to be managed in a manner that addresses the vulnerability of the societies through robust policies such as Integrated Flood Management with appropriate emphasis on both soft and hard solutions at various stages of the risk management cycle, including residual risks.

(l) Water utilities will have to make use of diverse portfolios of water sources and management strategies with an ability to move quickly and make and implement decisions. With increasing variability and extreme events of floods and long dry periods, all storage options, hard as well as soft, would have to be considered.

(m) Adaptive management that overcomes the challenges presented by uncertainties in various inputs to water management decision-making should be facilitated through flexible institutional arrangements, financial mechanisms, monitoring and capacity-building. Adaptive management allows adjustments to be made as more information is known.

(n) Continued operation of long-term monitoring networks and improved sensors deployed in space, in the atmosphere, in the oceans and on the Earth's surface are essential for understanding the current climate variability, for hydrologic trend analysis, for quantifying climate change and its impacts, and for improvements in the accuracy of forecasting methods. The effectiveness of adaptation strategies and actions requires continuous feedback and adjustments based on the information provided by monitoring networks.

(o) The current economic criteria are based on stringent benefit-cost tests or maximizing the internal rate of return. New economic evaluation and decision rules for infrastructure designed to cope with climate uncertainty should be more robust and resilient and should be able to adapt different decision rules.

(p) Multi-disciplinarily, multi-sectoral collaborations and incorporating principles of subsidiarity, decentralization and adaptive management would require building capacity, both institutional and human at various levels. Use of available climate information and probabilistic decision-making tools need to be encouraged at low and middle level management.

(q) The planning and design of new hydraulic infrastructure requires not only new hydrologic tools for dealing with a non-stationary climate, but also mechanisms for incorporating very uncertain and qualitative climate change scenario information, as well as a new socio-economic decision framework that can absorb this information as the basis for deciding among many costly options – from social, economic, environmental and equity perspectives.

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