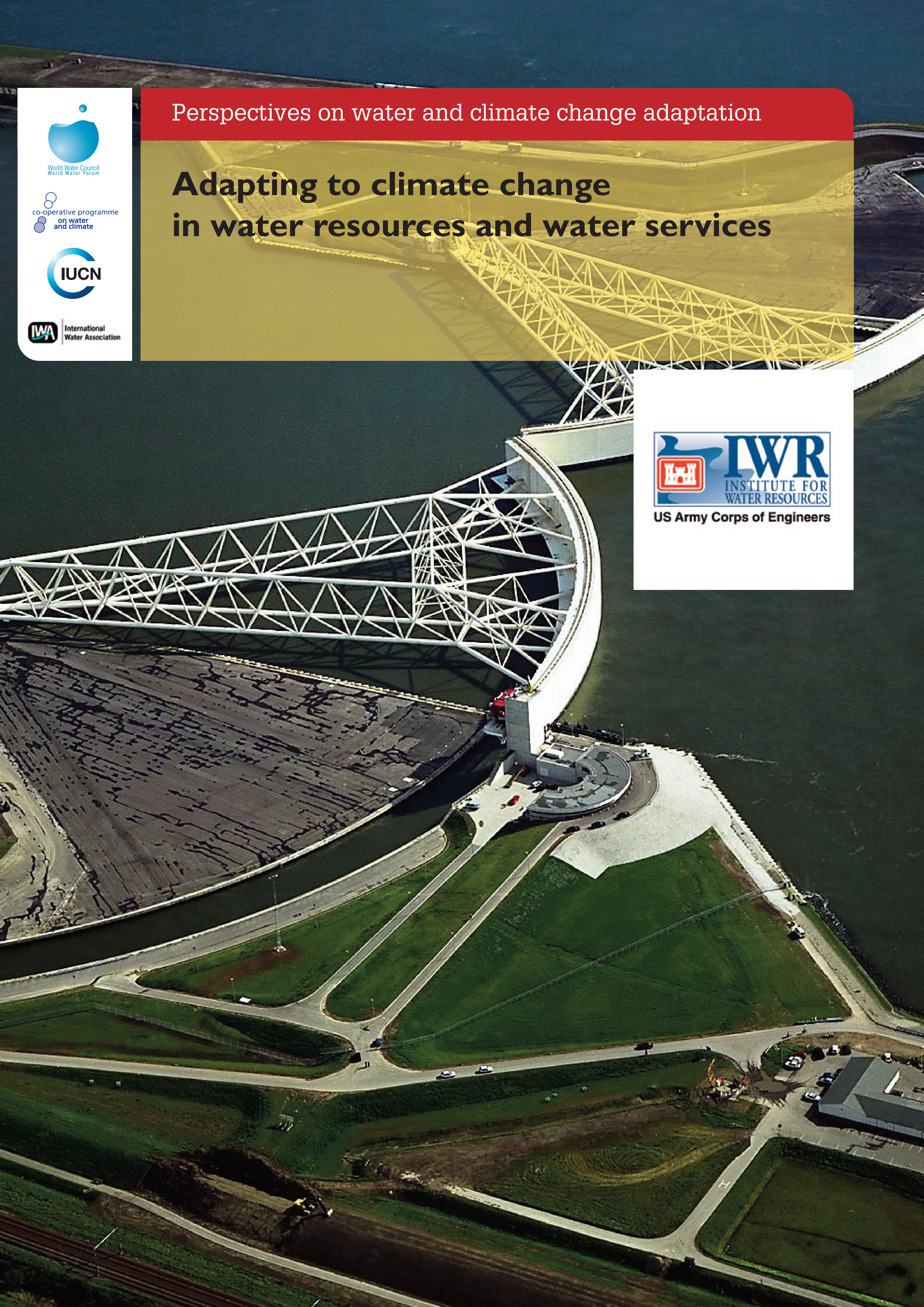

World Water Council
World Water Forum

co-operative programme
on water
and climate

IUCN

IWA International Water Association

Perspectives on water and climate change adaptation

Adapting to climate change in water resources and water services

IWR
INSTITUTE FOR
WATER RESOURCES
US Army Corps of Engineers

This Perspective Document is part of a series of 16 papers on «Water and Climate Change Adaptation»

‘Climate change and adaptation’ is a central topic on the 5th World Water Forum. It is the lead theme for the political and thematic processes, the topic of a High Level Panel session, and a focus in several documents and sessions of the regional processes.

To provide background and depth to the political process, thematic sessions and the regions, and to ensure that viewpoints of a variety of stakeholders are shared, dozens of experts were invited on a voluntary basis to provide their perspective on critical issues relating to climate change and water in the form of a Perspective Document.

Led by a consortium comprising the Co-operative Programme on Water and Climate (CPWC), the International Water Association (IWA), IUCN and the World Water Council, the initiative resulted in this series comprising 16 perspectives on water, climate change and adaptation.

Participants were invited to contribute perspectives from three categories:

1 **Hot spots** – These papers are mainly concerned with specific locations where climate change effects are felt or will be felt within the next years and where urgent action is needed within the water sector. The hotspots selected are: Mountains (number 1), Small islands (3), Arid regions (9) and ‘Deltas and coastal cities’ (13).

2 **Sub-sectoral perspectives** – Specific papers were prepared from a water-user perspective taking into account the impacts on the sub-sector and describing how the sub-sector can deal with the issues. The sectors selected are: Environment (2), Food (5), ‘Water supply and sanitation: the urban poor’ (7), Business (8), Water industry (10), Energy (12) and ‘Water supply and sanitation’ (14).

3 **Enabling mechanisms** – These documents provide an overview of enabling mechanisms that make adaptation possible. The mechanisms selected are: Planning (4), Governance (6), Finance (11), Engineering (15) and ‘Integrated Water Resources Management (IWRM) and Strategic Environmental Assessment (SEA)’ (16).

The consortium has performed an interim analysis of all Perspective Documents and has synthesized the initial results in a working paper – presenting an introduction to and summaries of the Perspective Documents and key messages resembling each of the 16 perspectives – which will be presented and discussed during the 5th World Water Forum in Istanbul. The discussions in Istanbul are expected to provide feedback and come up with sug• gestions for further development of the working paper as well as the Perspective Documents. It is expected that after the Forum all docu• ments will be revised and peer-reviewed before being published.

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Adapting to climate change in water resources and water services

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Adapting to climate change in water resources and water services

Access to potable water, sanitation and water for irrigation is already a serious problem in the developing world, especially in the vast semi-arid regions of Central Asia and Africa, and is expected to become even more serious as population growth and climate change exacerbates existing inadequate delivery systems and dysfunctional management institutions. The Millennium Development Goals (MDGs) have set very ambitious targets. The principles and practices of contemporary water management are well known and have adapted reasonably well to technological advances, institutional prerogatives and public preferences in the developed world. Yet the gap between water resources availability and needs grows inexorably in the developing world. Is it the failure of water managers, or the lack of adequate investment or failure to adopt new technologies, or is it a failure at a more elemental level; the failure of institutions and the technical capacity to implement solutions and to manage those investments wisely? There is a consistent storyline in the recent literature, such as the reports of the Intergovernmental Panel on Climate Change (IPCC; Bates et al, 2009) that: 'current water management practices may not be robust enough to cope with the impacts of climate change on water supply reliability, flood risk, health, agriculture, energy and aquatic systems.' The issue is whether it is water management that is not robust enough or the socio-political institutions within which water managers operate?

It stands to reason, based on the predictions of the Fourth IPPC (2007), that water resources will be among the most affected sectors by changes in climate. When coupled with population growth and serious economic circumstances, climate change is an additional, highly uncertain and variable factor that exacerbates the difficulties that developing nations have in achieving the MDGs, not even speaking of sustainable development. In order to set out on the glide path that is sustainable development, one must first climb out of poverty. Widespread poverty is perhaps the greatest barrier to systematic adaptation. The combination of high population growth and global economic disruptions, coupled with endemic poverty comprise an extraordinarily difficult set of barriers to overcome. A recent report that provides the status of 16 Sub-Saharan African countries in meeting the MDGs on water and sanitation (2006) clearly demonstrates how far these countries need to go simply to achieve the needs of the current population. Climate change, associated with global warming merely adds to those difficulties.

Water resources management, which has evolved with its core principles of adaptive management – i.e. 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, regulatory, financial and policy incentives. However, well-functioning institutions are needed to effectively administer this broad array of fairly complex, dispersed and expensive combinations of management measures. Hence, tackling the central issue of 'governance' is a key aspect of any strategy that intends to deal with climate change adaptation. IWRM 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, navigation/transportation) fashions its own set of management principles, rules and incentives that are maximized, often in conflict with one another.

Hence, the fundamental issue is not *whether* adaptation ought to occur, because it is already an integral part of water resources management, but when and how we must adapt more effectively. Those questions can be responsibly answered only by consideration of the costs and ultimate benefits of the adaptive measures, the risks and uncertainties inherent in any strategic planning initiative, and the availability of innovative technologies that can be brought on line in the near future through increased investments in research and development. Many problems exist today because water is misallocated, wasted and priced incorrectly. These defects are being slowly but steadily rectified in all aspects of water management. The deficiencies in the current water management systems should not be confused with an inability to adapt technically feasible solutions to changing conditions. The availability, relative effectiveness, and technical implementability of virtually all water management options is very well known. That is because water resources managers have been conducting economic and financial analyses of their projects and systems for nearly 50 years. Of course, the ultimate success depends on the capacity of any individual country to adapt the wide range of existing management resources.

This failure to differentiate between the technical feasibility of various adaptive measures and the relative capacity to implement well-known, accepted and relatively conventional water management practices, has lead to considerable confusion in the debate about the relative susceptibility of societies to the socioeconomic consequences of climate change. Ironically, developing nations in water-rich areas often have a more difficult time implementing conventional water supply measures to meet rapidly increasing water demand due to rapid population growth, than those countries in arid or semi-arid areas that are constantly faced with scarcity. In most countries that already have a water delivery system in place for irrigation, a reduction of 10 per cent of the water currently going to agriculture would meet the increasing demands of cities and industries through to the year 2025. In countries where such water delivery systems are poorly developed because of the abundance of naturally available surface water supply, their susceptibility may increase because of water pollution, increased demands and poor management practices.

Even without climate change, most developing nations will not be able to provide for the water resources needs of their growing populations because of lack of technical capacity, economic resources and socio-political instability. Clearly, we have to focus our attention on the developing world with strategies that fall into four basic categories:

1 Develop large-scale water infrastructure that will provide the needed buffering capacity, robustness and resilience to withstand the vagaries of climate variability and change;
2 Focus on ‘small is beautiful’ (and inexpensive) strategies for villages and remote rural areas, using appropriate technologies;
3 Concentrate on upgrading technical and institutional management capacities at all levels;
4 Continue to focus on developing and transferring technological innovations that, hopefully, will keep pace with population growth and provide an extra degree of resiliency to help coping strategies.

Ongoing efforts

Literally hundreds of efforts are underway at many levels of government, and within numerous international institutions devoted to preparing for adaptation to climate change (Heinz Center, 2006), especially in the water resources sector (e.g. Hashimoto Action Plan and the High-Level Expert Panel on Water and Disaster of the UN Secretary-General’s Advisory Board on Water and Sanitation (UNSGAB)). These initiatives, coupled with a strong emphasis on IWRM offers considerable impetus for implementing effective adaptation. Since the ‘Dialogue on Water and Climate’ (Kabat et.al, 2003), followed by the report of the Intergovernmental Panel on Climate Change (IPCC, 2007), there has been a sea change in attitude and realization that, regardless of how effective mitigation efforts might be in reducing greenhouse gases, the various water resources management sectors must at least engage in preparatory initiatives to cope with the anticipated adverse changes associated with predicted climate change impacts. Such influential institutions as the World Bank (2008) and the U.S. Army Corps of Engineers (2008) have initiated substantive programmes to review their existing infrastructure and pending investments with respect to adaptability to increased climate variability and potential changes. These institutions along with many other countries, such as the Netherlands and Japan, and the European Union and UN agencies, such as UNESCO, FAO, and UNDP, are engaged in a concerted and coordinated effort to provide technical advice for their own institutions, and client agencies and ministries, as well as providing the basis for capacity building for the rest of the world.

One such clear example was the United States response to Hurricanes Katrina and Rita, which exposed and highlighted the monumental challenges in responding to large-scale disasters. It has motivated the Corps of Engineers to take serious stock of its planning and engineering methods, and standards for evaluating, managing and responding to extreme events, and how they might be dealt with as part of climate scenarios that reflect different degrees of change from our historical expectations. It is often the case that great catastrophes, such as floods, droughts and infrastructure failures, catalyze both political and technical changes in attitude and performance and serve as the platform for a new generation of approaches. Because climate change, like drought, is a 'creeping', slowly evolving phenomenon, it will not serve to catalyze actions. Hence, the Secretary of the Army (2007) adopted a pragmatic 'proactive adaptive management' approach, comparable to the 'no regrets' philosophy espoused by many advocates of climate change adaptation, consisting of the following elements:

- Risk-based planning and design of infrastructure to account for climate uncertainties;
- Development of a new generation of risk-based design standards for infrastructure; responding to extreme events (floods and droughts);
- Life-cycle management of aging infrastructure;
- Vulnerability assessment of water infrastructure;
- Increased inspections, oversight and regulation of infrastructure during operation and maintenance;
- Increased research and development oriented towards climate change and variability;
- Develop improved forecasting methods for improved reservoir and emergency operations;
- Strengthen interagency collaboration for developing joint procedures and applied research for adapting to climate change;
- Strengthen emergency management and preparedness plans for all Corps projects and assist local communities in upgrading their plans and participation.

The World Bank's (2008) Strategic Framework on Climate Change and Development (SFCCD) recognizes water as the sector that will be most significantly affected by climate change. Each Bank region is likely to face a unique set of water-related climate change challenges, deriving from such impacts as: accelerated glacier melt; altered precipitation, runoff and recharge patterns and rates; extreme floods and droughts; water quality changes; saltwater intrusion in coastal aquifers; and changes in water uses. Potential adaptation strategies to the impacts of climate change on water resources have become central to the dialogue on water policy reforms and investment programmes with client countries. In order to complement regional efforts already underway, and to support future regional initiatives, the World Bank has undertaken a multi-year effort on Climate Change and Water. The main objective is to provide the analytical, intellectual and strategic assistance to regions for incorporating adaptation to climate variability change in their work programmes. The work focuses on water and water-related issues and investments, while addressing relevant linkages with other sectors. A particular focus will be on reducing the vulnerability of sector investments in both water delivery services and water management to the impacts of climate change. Final products will also include adaptation options for increased robustness and resiliency of water systems to climate variability/change, numerous case studies, and a series of thematic papers on water and climate change. It is hoped that this work will help enhance knowledge and understanding of both Bank water staff and client country professionals for making better-informed decisions regarding water investments.

As part of the Bank's assessment of its water portfolio, it conducted a review of the Bank's investments in water over the period 2006–09 taking into account the potential linkages to climate variability and change. More specifically, the objective was to:

1. Assess the World Bank's current portfolio and pipeline in the water sector, identifying the financing directed to the different water systems (services and resources);
2. Analyse how many Bank projects acknowledge climate variability or change in the project documents, including any mitigation or adaptation mentioned in project documents at the project design stage;

3 Identify the Bank's water portfolio and pipeline that may be exposed to the hydrologic aspect of climate change.

These three efforts alone, coupled with those of the European Union and individual nations such as the Netherlands and Japan, will serve as the backbone of a rapidly evolving practical adaptive management strategy.

Elements of adaptation to climate change

Many excellent reports and studies exist on adaptation to climate change for each of the sectors that are expected to be affected (water resources, forestry, ecology, agriculture, urban areas, etc.). Among the best, providing sensible advice on adaptation to climate change in the water resources sectors is the 'Dialogue on Water and Climate' (2003). Within these reports, a consensus has been reached that global warming will generate a series of foreseeable but highly uncertain hydroclimatic consequences, which will have impacts on water availability and, consequently, on water management.

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 it is 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, as well as reduce vulnerability and increase resiliency and robustness. But water managers are not the policy-makers and politicians who are responsible for establishing the enabling environment and providing the resources within which integration of different water-using sectors can be coupled with the economic and financial incentives to 'climate-proof' communities. Much of the available academic literature routinely confuses the two issues, while dismissing the confounding and more dominant effect of population growth, indirectly suggesting that water managers cannot keep up with the combination of reduced supplies and increased demands.

What can be done by water managers to prepare – i.e. set the stage for adaptation with the resources and options that are under their control? In fact many steps can be taken, based entirely on conventional methods and ideas. One does not need to resort to or depend on IWRM, even though the various approaches rely on concepts and elements that are comparable to the principles of IWRM. In the long term, having the institutional infrastructure that supports IWRM would clearly assist the implementation and sustainability of climate adaptation efforts, and ensure that they are compatible with and complement the broader goals of sustainable development. It is important to begin the pursuit of both initiatives, IWRM and climate adaptation, even though both are very complex and difficult even for developed nations to implement. The pursuit of a perfect complementary system should not divert the implementation of a series of useful preparatory 'first steps' in climate adaptation.

Integrated Water Resources Management (IWRM)

IWRM is the long-term 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 a few essential components/prerequisites:

1 National water management plan, and/or river basin management plan;
2 National water policy/ water code;
3 Harmonization of the policies, regulations and decisions at all levels of government;
4 Institutional infrastructure that can make consistent decisions and assure progress; manage and monitor resources and effectively deliver services;
5 Establishment of river basin management authorities.

The essential purpose of IWRM is to manage water more efficiently (use less water, more value per drop, conserve) and effectively (delivery of reliable services, improved performance in each sector). IWRM requires the harmonization of policies, institutions, regulatory frameworks (permits, licenses, monitoring), planning, operations, maintenance, and design standards of numerous agencies and departments responsible for one or more aspects of water and related natural resources management. Water management can work effectively (but not efficiently) in fragmented institutional systems (such as the federally-based systems of the United States, Brazil and Australia, for example), where there is a high degree of decision-making transparency, public participation, and adequate financial support for planning and implementation. It does not work well in most other cases where these prerequisites do not exist. Setting up the proper institutional framework is the first step towards IWRM.

Long-term, sustainable adaptation to climate change will require a series of progressively integrated measures to be implemented, consisting of infrastructure, policy instruments, economic adaptation and behavioral changes. These measures will vary with the degree of development in a particular country, and present anticipated vulnerability to the effects of climate variability, expressed as the change in the frequency and magnitude of floods and droughts. IWRM is the organized, orderly process by which adaptation to changes in population, demands, economic conditions and climate change can be addressed in a comprehensive manner. The foundations of IWRM not only serve contemporary problem-solving, but comprise the platform for adaptation in the future. However, having a well-developed IWRM infrastructure in place is *not a prerequisite* to initiating an adaptation strategy with the tools and resources at hand. The reality is that most advances in any human endeavor are made incrementally – in response to major events. Adaptive management is the more relevant and pragmatic approach that will serve most of the problems associated with contemporary water resources management.

Coping mechanisms and adaptation strategies

There is no single, clearly superior set of coping mechanisms and adaptation strategies for water management – whether for contemporary climate variability or for adaptation to climate change. 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 before they can move on to preparing for the more uncertain demands associated with climate change.

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. However, other combinations of nonstructural measures (conservation, pricing, regulation, relocation, etc.) 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 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. However, depending on the criteria used to determine the 'best' choices (economic efficiency, risk reduction, robustness, resiliency, reliability) it is clear that an emerging technology, which has the potential to improve virtually all forms of water management, is 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 USA. 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 and in areas of salinized and brackish water. The combination of these two imminent technological breakthroughs alone, forecasting and biotechnology, would play a major role in aiding societal adaptation to climate change around the world, especially in developing nations.

An essential adaptation mechanism is the formalization of transboundary water allocation rules and existing storage reallocation. Both require an institutional framework for IWRM, since allocation deals with the most fundamental issue of water use priorities in times of crises, and how much water is assigned to the various purposes within each country, region and specific reach of the river. Agreeing on the terms for water allocation leads to the development of the more basic water management rules and operations for each reservoir and river. These rules require a full analysis of the water balance and withdrawals, which in turn require monitoring and data collection. Water allocation is a prerequisite for the efficient and effective implementation of all other water management measures and is, therefore, the fundamental component of any adaptation strategy to climate change at the regional, national and river basin scales.

Adaptive management of existing infrastructure

There are two dimensions to adaptation: the numerous changes that can be implemented readily as part of an ongoing adaptive management approach, and which will serve to increase the resiliency and robustness of existing water management systems, and; the fundamental design changes that are needed to accommodate highly uncertain future climate scenarios for new hydraulic infrastructure. 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 would be in the two sectors that are most vulnerable to climate change and are critical to human settlements and food security – agricultural irrigation and flood plain management and flood hazard/damage reduction.

The functions that are dependent on a sound knowledge of flood and drought frequencies - as part of highly uncertain climate change scenarios as the basis for changes in hydraulic and hydrologic design criteria for planning new long-lived hydraulic structures - will require a fundamentally new approach to adaptation that requires a substantial investment in research and collaboration among the principal practitioners around the globe.

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' (National Research Council, 2004). Adaptation to climate change is a merely a cousin of adaptive management – a continuous process of adjustment and flexible adaptation that attempts to deal with the increasingly rapid changes in our societies, economies and technologies. Adaptive management is perfectly suited to much of the immediate efforts needed for operational adjustments in the current infrastructure; changes in processes and demands, and maintenance and rehabilitation of existing infrastructure – particularly for irrigation systems and flood risk management in the floodplains 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 productivity and water use efficiency, and reducing flood damage losses.

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

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.

The fact is that the foundation of climate adaptation rests in the hydrologic methods that are currently used to plan, design, operate and maintain the present hydraulic infrastructure. Hence, the water resources sector is inherently better prepared than most to respond to climate change, notwithstanding the fact that the capacity and capabilities to apply these methods in the developing world are lacking. The only new dimension that is added to what is typically an inherently uncertain water management system, is the added uncertainty of climate change impacts and its influence of hydrologic extremes. Long-term climate predictions of 20-, 50- and 100 years hence are simply unsuitable to the contemporary needs of planners, designers and water systems operators. What is needed today are methods that can provide more reliable short-term, inter-annual forecasts of 30-, 60- and 90-day hydrologic variability.

However, little progress has been made in developing new practical techniques for analysing hydrology under climate uncertainty, which are the foundations of all water management – reservoir operations, water allocation, risk and reliability analysis, design of water infrastructure, and flood insurance and floodplain management. The fundamental mission of any water management agency is to protect its customers from the extremes and uncertainties of climate variability. Climate change adds another dimension of uncertainty, for which we have few operational tools. It is of paramount importance that water management agencies, throughout the world, deal with the practical ramifications of climate change impacts, and that we collaborate across national, federal and state agencies to develop sensible strategies that anticipate various scenarios where these trends are expected to intensify. Even within the bounds of historical climate variability there are difficult decisions surrounding basic questions whose complexity will inevitably be compounded with global warming. At any given region or location, planners and designers have to determine:

- How high should a levee be, and what is the risk to those living and working behind it?;
- How to characterize and identify a 100-year floodplain?;
- How to adaptively manage a reservoir to accommodate an increasingly uncertain spring runoff?;
- How much storage in a reservoir should be allocated to future irrigation versus other competing future needs?;
- What criteria should be used to ‘recertify’ flood mitigation structures where the flow frequencies have changed or are in the process of changing; and,
- How should our contemporary ideas on life-cycle infrastructure management and performance accommodate our evolving scientific understanding of climate change?

Water resources management is essentially bounded by how the extremes – floods and droughts – are defined, and methods for reducing the risks to society. Virtually all major infrastructure requires some estimate of what the extreme events have been historically, as the probabilistic basis for design, setting flood insurance rates, crop insurance, hurricanes, etc. In many cases the extremes and changes we are experiencing are still within the ‘norms’ of natural climate variability, within which our existing water resources infrastructure was designed to accommodate such an order-of-magnitude of variability. Yet, the climate change modeling community is convinced that there are ‘signals’ of a shift in the climate means and trends. As a preparatory action, the operating agencies and the science community need to engage their researchers, planners and reservoir operators with those of other agencies, to try to better understand the nature of these changes and to start to develop methods that could help our planners and operators begin to deal with these shifting trends. The water resources public works planned today must be robust and resilient to future extreme events and designed with an added degree of uncertainty in their re-occurrence frequency and/or magnitude due to global warming. The inventory of infrastructure that we manage today must likewise be maintained and, perhaps, upgraded to provide an extra degree of safety, resiliency and reliability to address these uncertainties. We need a ‘paradigm shift’ and a new class of tools and techniques for planning, designing and operating our water infrastructure if we are to be successful in adapting to climate change.

Though a majority of water management decisions are made at the local project level, requiring fairly specific design standards and models that can address climate uncertainty, there is an additional important aspect to this effort which can deal with watershed and river basin planning and evaluation issues (including transboundary water allocations). This regional level of analysis requires a higher order level of hydroclimatic analysis (through regional GCMs) which will establish the likely range of regional changes, in terms of discharges, probable maximum floods, probable maximum precipitation, flood and drought frequencies, and new ranges for flood plain management purposes and safe yield reliability calculations for water supply and irrigation. This level of analysis is essential as part of IWRM, so that all the subsidiary decisions made at the watershed and local levels are using the same baseline for planning and evaluation of alternatives, along with reservoir operations in a complex river basin system.

For example, the Corps of Engineers has long known that Category 5 hurricanes of the magnitude of Katrina were anticipated, even within what we consider 'normal' climate variability, but no one could predict the frequency of such events, and still more difficult is how the magnitude and frequency will be altered under different climate change scenarios. Society and the engineering profession, through a historical accumulation of experience, laws, engineering practices and regulations, have defined a narrower acceptable range of 'expected' events to which it chooses to adapt – hence we have the 100-year floodplain 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. 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 determined criteria made on the basis of empirical or simulation modeling. Neither GCM models nor IPCC reports can provide such a determination. 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 each society – whether it be for new drugs, nuclear power plants or water infrastructure.

While a formal, systematic approach to climate change adaptation (CCA), coupled with IWRM is an ideal goal, the reality is that any major event in a nation – any large damaging flood or drought or infrastructure failure - can and should serve as the catalyst for a series of organized incremental changes in water management to bring it closer to a systematic adaptive management footing for climate change. Even if only some of the essential components of the IWRM institutional infrastructure are in place, there are opportunities to begin CCA at almost any level of government or entry point in the existing water management infrastructure. There is an impressive array of perfectly sound and workable water resources management measures that are routinely used and can be mobilized into a more coherent and 'proactive adaptive management' preparatory approach. This is comparable to a 'no regrets' strategy suggested in many studies. The difference is that adaptive management has a specific definition and rationale, the principles of which should be applied to climate adaptation. It is preparatory, because it is not clear yet that climate change can be detected in the hydrologic record. Even though the GCM models predict certain changes, the actual evidence for such changes is still ambiguous – many long-term observational records, upon which water management decisions are based, do not yet support evidence of non-stationary trends. Hence, an adaptive management strategy is the pragmatic way to deal with this evolving and highly uncertain phenomenon, based on models that are yet in their infancy.

If societies cannot deal with contemporary and foreseeable water management needs, they most certainly will not be able to cope with highly uncertain climate change consequences. Contemporary adaptation is a necessary prerequisite for dealing with climate change uncertainty. Adaptation can effectively begin with existing conventional methods, tools and resources. Most systems can achieve quite a bit of adaptive efficiencies by rethinking and reorganizing existing methods, practices and processes. As climate change and variability becomes more extreme, newer, more innovative technologies, economic incentives and financial instruments and institutional arrangements will have to be introduced. There are essentially five ways that water managers have of adapting to climate change:

1. Planning **new investments**, or for capacity expansion (reservoirs, irrigation systems, levees, water supply, wastewater treatment);
2. **Operation, monitoring and regulation** of existing systems to accommodate new uses or conditions (e.g. ecology, climate change, population growth);

3. Maintenance and **major rehabilitation** of existing systems (e.g. dams, barrages, irrigation systems, canals, pumps, etc.);
4. Modifications in **processes and demands** (water conservation, pricing, regulation, legislation) for existing systems and water users;
5. Introducing new **efficient technologies** (desalting, biotechnology, drip irrigation, wastewater reuse, recycling, solar energy).

Coupled with the basic set of adaptation strategies and options, there are a series of sensible principles to guide contemporary water resources managers in the evaluation, selection, and implementation of appropriate adaptive response strategies. These adaptation strategies should be undertaken when they:

- are beneficial for other reasons and justifiable under current evaluation criteria;
- are economically efficient and cost-effective;
- service multiple social, economic, and environmental purposes;
- are adaptable to changing circumstances and technological innovation;
- are compatible with the concept of sustainable development; and
- are technically feasible and implementable.

Monitoring systems

Long-term monitoring networks are essential for detecting and quantifying climate change and its impacts. The effectiveness of adaptation strategies and actions – i.e. adaptive management – requires continuous feedback and adjustments based on the information provided by these networks, including improved sensors deployed in space, the atmosphere and the oceans, and the earth's surface. To be useful for water management, a good part of the monitoring networks need to be emplaced in locations relevant to water managers – i.e. in watersheds important to municipal water supply, or in especially hydrologically-sensitive areas.

Monitoring networks are essential for hydrologic trend analysis and improvements in the accuracy of forecasting methods. Detecting statistical shifts in trends of precipitation and streamflow are key to the management of existing water resources systems and the design of new systems. The state of General Circulation Model projections are such that they are significantly inconsistent with observations, and as such cannot be used as reliable information for water management needs – neither current operational needs nor design of future infrastructure (Brekke et al, 2009).

Operational changes

Operational changes are inherently oriented towards improving the use and performance of the existing water resources delivery systems for all of its designed and de facto uses. Most reservoirs in the USA undergo periodic reviews of their operating rules, either as part of new and expanded hydrologic records, or as new uses or purposes are added (e.g. recreation, environmental flows, protection of endangered species, etc.). 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 flood and drought frequency analyses based on new methods and extended data, along with scenarios based on GCMs that would test the robustness of the operating system.

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 if the reliability of the forecasting methods could be improved. Conjunctive use of groundwater and surface water as apart of a more sophisticated water management strategy is another aspect of operational changes that can be implemented now with fairly conventional methods and techniques, associated with an adaptive management plan (monitoring, feedback and adjustment to operating rules).

Vulnerability assessment

It is useful to differentiate hydrologic runoff *sensitivity* to climate change from that of water management *vulnerability* and societal *susceptibility* to economic disruptions and dislocation as a consequence of climate change. Hashimoto et al. (1982a, 1982b) introduced a taxonomy to account for risk and uncertainty inherent in water resources system performance evaluation. It is clear that the five terms listed below simply represent a set of descriptors that characterize and extend the key components of more traditional engineering reliability analysis, i.e. they focus on the sensitivity of parameters and decision variables to considerations of uncertainty, including some aspects of strategic uncertainty. The terms are:

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

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

Resiliency – how quickly a system recovers from failure (floods, droughts);

Vulnerability – how severe the consequences of failure may be;

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

The relative *vulnerability* of a water resources system is, therefore, 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, which 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. These processes include:

- Assess existing statutes, policies and regulations for dealing with extremes and contingencies – who has the authority and responsibility for what?;
- Who is responsible for climate adaptation planning?;
- Who operates and maintains existing water infrastructure? Is it at capacity? Can it serve projected needs? What is needed over next 10–20 years?;
- Assess socioeconomic scenarios of growth and development – what does the future look like? How will future demands for resources be met? What is role of water?;
- Assess vulnerability to current climate variability – floods and droughts. How will this change under future climate scenarios, and growth in 2050?

Emergency preparedness and response

In the end, political will and substantial financial resources will be 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 be a devastating drought, flood, typhoon or hurricane. Emergency preparedness and response 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, levee overtopping, etc.) 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.

Technological advances

One of the obvious investments in technological development that is expected to have immediate payback is improved forecasting 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 risksharing programmes. But forecasting requires much more investment in scientific research, as well as installing and maintaining hydroclimatic 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. These technological advances are essential for climate change adaptation, yet do not require complex institutional systems for implementation – i.e. they can be implemented without a fully organized 'integrated water resources management' (IWRM) strategy and institutional infrastructure.

The way forward

The focus of climate change studies must begin to shift from generic global impact assessments to more focused adaptation and response mechanisms, and deal with the socioeconomic and political dimensions of difficult resource management tradeoffs. No individual water management agency and affiliated research institute can deal with the problem of developing a suite of new principles and tools that water managers and design engineers can use effectively to adapt to climate change. The issues are too complex and the problems are too diverse, ranging from agricultural engineering to spillway design. At the global level, every institution from the World Bank to the Global Water Partnership is struggling with comparable issues, which are intertwined with sustainable development and IWRM.

An internationally coordinated and collaborative applied research and development effort needs to be undertaken by a few select water research centres that routinely deal with practical implementation issues for water management. It is important that the research institutions engaged in this effort be associated with operating issues of water management agencies, rather than approaching this as an academic exercise or an IPCC-type effort. The issues that confront water managers and infrastructure designers require quite pragmatic approaches and tools – even if they are transitional in nature. It is important that the methodologies developed be as useful as possible, derived from existing conventional methods for risk and uncertainty analysis, and which could be used by mid-level career practitioners in a typical agency. The methods must strive for uniformity and consistency.

A new 'paradigm shift' is required in the methods that are used for justifying new water resources investments and projects, which includes very different economic decision criteria. The planning and design of new hydraulic infrastructure requires not only new hydrologic tools for dealing with a non-stationary climate, and mechanisms for incorporating very uncertain and qualitative climate change scenario information, but also a new economic decision framework that can absorb this information as the basis for deciding among very costly options – from a social, economic, environmental and equity standpoint. 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 – i.e. be more robust and resilient – need to apply different decision rules, such as maximizing risk-cost effectiveness or minimizing risk-cost.

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