Practical approaches to water management under climate change uncertainty

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Abstract Water resources management is in a difficult transition phase, trying to accommodate the large uncertainties associated with climate change, while struggling with implementing a difficult set of principles and institutional changes associated with integrated water resources management (IWRM) and adaptive management (AM). Water management is the principal medium through which many of the projected impacts of global warming will be felt and ameliorated. Many standard hydrological practices, based on assumptions of a stationary climate and variability, can be extended to accommodate numerous aspects of climate uncertainty. Adaptations of various strategies developed by the water management profession to cope with contemporary uncertainties and climate variability can also be effectively employed during this transition period, as a new family of hydrological tools and better climate change models are developed. "Robust decision-making" is among the new approaches being advocated for planning and designing water resources infrastructure under climate uncertainty.

Key words climate uncertainty; integrated water resources management; adaptive management; robust decision-making

INTRODUCTION

In order to address the issue of climate change uncertainty in the context of water resources decision-making within the broader framework of IWRM, one must ask what is the nature of those decisions. Even within the bounds of historical climate variability there are difficult decisions that routinely surround basic management actions associated with the design of new infrastructure, reservoir operations, drought management or flood fighting. The complexity of these decisions will inevitably be compounded by global warming, because a great deal more uncertainty associated with unknown states of future climate is introduced into the decision-making process. Decision-makers, politicians and the public at large, all of whom are expected to participate in modern water management decision-making at some level, have a difficult enough time with standard concepts of a 100-year flood plain or a category-5 hurricane storm surge. 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 hydrological and precipitation phenomena:

- How high should a levee be, and what is the risk to those living behind it?
- How to characterize and identify a 100-year flood plain?
- How to manage a reservoir to accommodate uncertain spring runoff?
- How much storage in a reservoir should be allocated to irrigation *versus* other competing future needs?
- How to size the spillway for a rare flood?
- 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 procedures on life-cycle infrastructure management and performance accommodate our evolving understanding of climate change?
- What discount rate should be used for benefit–cost analysis when designing for the "precautionary principle"?
- What flood/drought frequency distribution should be used in a particular analysis to accommodate climate uncertainty?

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. Virtually all major infrastructure requires some estimate of what the extreme events have been historically, as the probabilistic basis for design; for setting flood insurance rates; crop insurance, defining flood-plain zones and designing storm sewers and highway culverts, etc. In most cases, the extremes and changes we are experiencing are still within the "norms" of natural historical climate variability. Our existing water resources infrastructure was designed to accommodate such order-of-magnitude of variability. In fact, standard engineering practices account for the uncertainties by designing redundancy to account for the uncertainties. Hence, "levee freeboard" was added onto a "standard project flood" to accommodate the uncertainties associated with historical climate variability involved in designing levee systems.

This was the equivalent of applying an early version of the "precautionary principle" to deal with the unknowns – i.e. those aspects of hydrological phenomena that went beyond conventional risk and uncertainty analysis. Climate uncertainties are not really uncertainties – they are true unknowns, and hence incapable of being estimated based on the current state of climate modelling, making the estimation of these extremes virtually a meaningless exercise for the purposes of water management needs. So, if we are to deal with climate change, a substantially different water management approach needs to be devised – yet based on a foundation of existing principles and evaluation techniques. This approach, essentially an adaptation of existing proven principles and techniques, shall be termed "robust decision making" – a process designed to accommodate uncertain scenarios with evaluation and project justification principles that focus less on optimal outcomes and more on "satisficing" – i.e. producing robust solutions.

The design of new water infrastructure projects presents the biggest challenge in the current circumstances, i.e. the transition period, as the life of a typical project is usually 50 years or more, and encompasses the period when climate change impacts are expected to become more severe. Standard hydrological methods are still useful, though carefully selected climate scenarios can be applied to test the robustness of the performance of various alternative designs to determine the "best" (most risk–cost effective) design. However, economic decision criteria and evaluation practices would need to be revised in conjunction with the changes in hydrological analyses. For example, the choice of the discount rate in any economic analysis, whether it be internal rate of return or classical benefit–cost analysis is the single most important determinant of the economic viability of a water project.

CHRACTERISTICS OF WATER MANAGEMENT

According to the IPCC (2007), climate change is a significant threat to all nations and, in particular, developing nations that are dependent on agriculture for subsistence. Every nation is vulnerable to rare and extreme flood and drought events – the USA is no exception, as was demonstrated by the devastation of hurricane Katrina. The reality is that water management systems are not designed to protect against the full range of possible expected extreme events under what is understood to be contemporary climate variability. They are designed to minimize the combination of risks and costs of a wide range of hazards to society. This risk–cost balance is constantly being adjusted by societies – that is why we have relatively safety standards for flood and drought infrastructure reliability set at about a 100-year return period – they approximate that historically-determined risk–cost optimum for our systems. Of course, as population density in urban areas increases, these standards may have to change, and begin to approach the risk-averse standards of The Netherlands and Japan. The setting of new design standards and planning criteria are probably the most important aspects of any adaptation strategy. Since the destructive Mississippi River floods of 1993, there has been a movement to increase the flood protection standards of major urban areas in the flood plains to about a 500-year level of flood protection (Interagency Floodplain Management Review Committee, 1994).

For the past 50 years, the USA has followed a path of what could be termed "autonomous adaptation" to climate variability and change, which has proved to be reasonably effective with respect to water resources management (Lins & Stakhiv, 1998; Lettenmaier *et al.*, 1999; Olsen, *et al.*, 1999). There have been very few failures of the nation's water management infrastructure – i.e. where the infrastructure failed before its design capacity was exceeded. It should be remembered that most of the nation's large water infrastructure (locks, dams, levees, irrigation canals and conveyance tunnels) was built in the period between the 1930s and the 1970s – well before the era of sophisticated modelling, risk and reliability analysis and an adequate database for determining risk and uncertainty associated with climate variability. Yet the structures stand and have performed effectively through a wide range of unanticipated climate variability – in other words they are remarkably robust and resilient.

Though the science of hydrology, hydraulic engineering, watershed modelling and data collection have improved dramatically since the 1970s, especially with the advent of satellite-based data, the dominant changes that influence the design of contemporary hydraulic structures since 1970 have come from the multi-objective planning paradigm, rather than changes in engineering design standards and criteria. The basic standards used for designing hydraulic infrastructure – notions like the "probable maximum flood" (PMF) for spillway design; or application of a 100-year return period as the basis for traditional levee design and the flood insurance programme – are based on hundreds of years of engineering experience and empirical analysis. Planning and evaluation principles have changed dramatically during the past 50 years, influenced largely by the ideas of the Harvard water programme (Maass *et al.*, 1962), and implemented through the planning guidance of the US Water Resources Council (WRC, 1973, 1983). The principal purpose of planning, though, was not to design reliable, robust and resilient hydraulic structures, but to design projects and programmes that served a more diverse range of social needs, and adequately accounted for the direct and indirect economic, social and environmental costs, and which optimized net economic benefits, subject to environmental constraints.

The pressure from academia to revise the basic planning and evaluation guidelines of the federal agencies to design more economically efficient projects that encompassed a wider range of purposes, services and outputs, actually reduced the operational reliability, robustness and resiliency of projects by eliminating a range of engineering "safety factors" that typically accounted for the hydrological uncertainties and unknowns and ignorance associated with a highly variable climate, poor models, and inadequate databases. Ironically, the focus on risk and uncertainty analysis, together with multi-objective optimization effectively reduced much of the engineered redundancy of many projects that were based on the original standards-based paradigm, which explicitly acknowledged the ignorance of hydrological and hydraulic engineers with respect to climate variability.

These safety factors actually constituted an early and unacknowledged version of the "no regrets" principle, as well as the "precautionary principle". Early engineers knew that there was persistence in the hydrological record; that there were trends and multi-decadal fluctuations, and understood that there were events that were much larger and more extensive than in the short hydrological records they typically dealt with. They planned for the unknowns by designing system redundancy and adding safety factors. That is why so many projects have functioned under a much wider range of conditions and purposes than designed for, and have repeatedly been adapted to a broader range of needs and conditions by sequential reallocation of storage and changes of operating rules – i.e. they have more resilience and robustness than anticipated (Fiering, 1982; Rogers & Fiering, 1986). Furthermore, the addition of numerous other social, cultural and ecological requirements and constraints, along with a host of new project purposes that were never authorized by legislation (recreation, ecological flows, flood plain benefits, etc.) actually reduced the degrees of freedom that operators had to manage such projects in emergencies, and further decreased the robustness and resiliency of each water management infrastructure system. Ironically, but not surprisingly, sustainable development principles have reduced the flexibility of water managers to operate and prepare for uncertainties, contingencies and emergencies, and has created what Hashimoto *et al.* (1982) have termed "brittle solutions".

CONVENTIONAL WATER RESOURCES DECISION-MAKING

What constitutes water sector decision-making? Although hydro-climatological 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-hydrological 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 hydrological information.

Despite the best attempts to extract the most information possible from the current suite of general circulation models (GCMs) for peering into the future, the best that can be said is that all the models are fairly uniform in the unidirectional increase in temperatures, but offer very little reliability for forecasting precipitation or runoff. What is much more uncertain, verging on the edge of unknowns, is how this translates into precipitation, evaporation, frequency and intensity of droughts, floods, tornados or hurricanes. The information currently available from GCMs is simply inadequate for most operational and design aspects of water sector decisions, and is not expected to be useful for at least another decade. So, we have to resort to extending existing approaches to substitute for the lack of usable information from the GCMs.

Society, and the engineering profession, through a historical accumulation of experience, laws, engineering practices and regulations, has defined a narrower acceptable range of “expected” events to which it chooses to adapt – hence 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. 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. 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 is for new drugs, nuclear power plants or water infrastructure.

The water resources management sector has developed strategies to deal with periods of high demand and low water availability. There are essentially five ways that water managers have of adapting to climate variability and change:

- Planning **new investments**, or for capacity expansion (reservoirs, irrigation systems, levees, water supply, wastewater treatment).
- **Operation, monitoring and regulation** of existing systems to accommodate new uses or conditions (e.g. ecology, climate change, population growth).
- Maintenance and **major rehabilitation** of existing systems (e.g. dams, barrages, irrigation systems, canals, pumps, etc.).
- Modifications in **processes and demands** (water conservation, pricing, regulation, legislation) for existing systems and water users.
- Introducing new **efficient technologies** (desalting, biotechnology, drip irrigation, wastewater re-use, recycling, solar energy).

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 (Kabat *et al*., 2003).

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.

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 or prerequisites:

- national water policy which lays out roles, responsibilities and management objectives;
- national/regional/river basin water management plans that are consistent with national water policies;
- river basin commissions that implement and manage resources according to plans that are updated periodically;
- enabling regulatory and institutional regimes, with enforcement mechanisms; and
- coordinated federal/state/local management.

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 USA, Brazil and Australia, as examples); 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.

Adaptive management

Adaptive management (and its cousin the "precautionary principle") are key concepts that are central to the management of the vast network of existing water infrastructure. The keystone of adaptive management is a much improved meteorological and hydrological data network. Flood and drought contingency preparedness and recovery operations are the leading edge of any adaptive management strategy that is inherently geared to dealing with uncertainty of climate variability and change, and dependent on better forecasting and real-time data collection and analysis. Improvements in seasonal and intra-annual forecasts would offer the greatest positive changes to a broad array of water management functions – especially for agricultural irrigation, which uses approximately 80% of the freshwater resources of the globe, and is essential to most economies of the developing world.

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 technological changes. 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 flood plains of river basins. These are the two water management sectors that would provide the largest and most immediate pay-offs in climate change adaptation, by reducing the vulnerabilities of existing systems, improving productivity and water use efficiency, and reducing flood damage losses. Adaptive management may be the most effective way of dealing with future climate impacts under the current evaluation procedures and high degree of uncertainty (Stakhiv & Pietrowsky, 2009).

Vulnerability assessment

It is useful to differentiate hydrological runoff *sensitivity* to climate change from water management *vulnerability* and societal *susceptibility* to economic disruptions and dislocation as a consequence of climate change. Hashimoto *et al.* (1982) 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. These 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.

Resilience – 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, then, is a function of hydrological *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, however, 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 hydrological variability, but more as a function of an inadequate institutional infrastructure required to manage those resources. IWRM, coupled with adaptive management, are the two most effective mechanisms to deal with the uncertainties associated with social susceptibility. 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:

- 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 socio-economic scenarios of growth and development – what does the future look like? How will future demands for resources be met? What is the role of water?
- Assess vulnerability to current climate variability – floods and droughts. How will this change under future climate scenarios, and growth in 2050?

ADAPTING A NEW PARADIGM FOR DECISION-MAKING

To more effectively accommodate the new version of the "precautionary principle", together with the broader aims of sustainable development, there will have to be a paradigm shift from the deterministic view embodied in the *Principles and Guidelines* (WRC, 1973, 1983), based on a view of a relatively stationary climate, to a much more flexible set of multi-objective evaluation principles and procedures that more appropriately account for the full range of social, environmental and regional economic dimensions of water infrastructure under a wide range of uncertain climate scenarios. It may require an end to the era of rational analytical optimization to one where robustness and resiliency features are built into water projects – especially more flexible operational elements of a project. But the fundamental changes must come in the economic evaluation principles that are used for project justification; e.g. changing decision rules from "maximize net benefits" to "minimize risk–cost". 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 – needs to adapt different decision rules, such as maximizing risk–cost effectiveness or minimizing risk–cost. The process has already begun in many federal agencies in order to accommodate the uncertainties associated with planning and designing infrastructure under climate change uncertainty.

There are many improvements in existing conventional approaches that can be made, which fall under the general rubric of "robust decision-making" (RDM). RDM is a framework for making decisions with a large number of highly imperfect forecasts of the future. RDM relies on many plausible futures (e.g. climate change models, historic information, tree-ring data, etc.), and then allows analysts and decision makers to identify a series of near-term and long-term actions (options) that are robust across a very wide range of futures. Rather than rely exclusively on a single future or a probabilistic forecast of a possible future, the approach asks what can be done today to set the stage and shape a more desirable future (Lempert *et al.*, 2010). The strategy has three complementary components:

– Seeking robust rather than optimal projects or strategies (this requires a substantial revision of current economic and optimization decision rules routinely used in water resources management).
– Employ adaptive strategies to achieve robustness (near-term strategies are explicitly designed with the expectation that they will be revised as better information becomes available).
– Use computer-aided analysis for interactive exploration of hypotheses, options and possibilities.

This sort of strategy has been advocated for the past few decades by water resources practitioners and academicians. For example, Rogers & Fiering (1986) noted, in an evaluation of how systems analysis and optimization models were being employed by the USA federal water management agencies, that there were practical and political limitations on the use of such advanced techniques, and that there were many solutions that were near the global optimum. When coupled with the large uncertainties involved in much of the input data, the use of such models for practical public decision making was problematic, indeed. They concluded by urging that the "*… use of optimizing models be softened in favor of systematic analysis. This is consistent with the earlier concept of satisficing proposed by Simon (1957), which looks for solutions that maximize the probability of achieving acceptable (satisfactory) outcomes*", rather than searching for optimal, economically efficient solutions. This advice is even more relevant when confronted with climate change uncertainties and unknowns. A practical version of RDM has been developed by water resources planners in the US Corps of Engineers and applied successfully under the label of *Shared Vision Planning* (Werick & Palmer, 2008). It has been used most directly for climate change adaptation in two Great Lakes regulation studies for the Lake Ontario-St Lawrence system (LOSL Board, 2006) and the Upper Great Lakes (IUGLS Board, 2009).

PRACTICAL RECOMMENDATIONS

Because climate change, like drought, is a "creeping", slowly evolving uncertain phenomenon, it will not serve to catalyse actions in a politicized world that has profound difficulties in dealing with uncertainties that potentially require huge investments upfront to avoid unknown risks. To deal with the unique circumstances of this type of phenomenon, the US Army Corps of Engineers (Secretary of the Army Congressional Testimony, 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 ageing 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.

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