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PRAGMATIC APPROACHES FOR WATER MANAGEMENT UNDER CLIMATE CHANGE UNCERTAINTY[1]

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ABSTRACT: Water resources management is in a difficult transition phase, trying to accommodate large uncertainties associated with climate change while struggling to implement a difficult set of principles and institutional changes associated with integrated water resources management. Water management is the principal medium through which projected impacts of global warming will be felt and ameliorated. Many standard hydrological practices, based on assumptions of a stationary climate, can be extended to accommodate numerous aspects of climate uncertainty. Classical engineering risk and reliability strategies developed by the water management profession to cope with contemporary climate uncertainties can also be effectively employed during this transition period, while a new family of hydrological tools and better climate change models are developed. An expansion of the concept of "robust decision making," coupled with existing analytical tools and techniques, is the basis for a new approach advocated for planning and designing water resources infrastructure under climate uncertainty. Ultimately, it is not the tools and methods that need to be revamped as much as the suite of decision rules and evaluation principles used for project justification. They need to be aligned to be more compatible with the implications of a highly uncertain future climate trajectory, so that the hydrologic effects of that uncertainty are correctly reflected in the design of water infrastructure.

(KEY TERMS: climate uncertainty; climate variability; integrated water resources management; adaptive management; robust decision making; economic decision rules.)

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INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), climate change is a significant threat to all nations and, in particular, developing nations that are dependent on agriculture for subsistence. The most significant implication of climate change for water resources management includes the very real possibility that there will be even greater variability – that is, floods and droughts will become more frequent and of greater magnitude and longer duration. The paleo-climate record of the United States (U.S.) shows long cycles of persistent

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flood and drought periods, with multidecadal intense drought periods that are far longer than anything experienced in the last 100 years of collected data (Laird *et al.*, 1996; Woodhouse and Overpeck, 1998). If one believes that climate change is real and that it is reasonable to expect that frequency, duration, and intensity of floods and droughts might be increasing as well, then an appropriate response would be to ensure that future water management infrastructure is planned and designed to better manage those hypothetical increased risks. Simply put, the projected increases in climate variability will likely require more robust water infrastructure to deal with both the rapidly expanding water supply requirements of growing populations and predicted increased risks associated with climate change.

Unfortunately, while many U.S. agencies, as well as international donor agencies, are promoting the highly uncertain climate change projections of the IPCC and devising numerous questionable methods for regional vulnerability assessments (Kundzewicz and Stakhiv, 2010), they are not simultaneously promoting a commensurate framework of planning and design methods for a new generation of more robust, reliable, and resilient water resources infrastructure that would more effectively deal with those highly uncertain increased risks. Instead, there is a persistent focus on what is termed the "soft path" to climate adaptation (e.g., Gleick, 2002), which advocates that economic growth and development can be decoupled from water resources development, emphasizing such generic strategies as water conservation, water use efficiencies in agriculture, and "learning to live with floods and droughts."

For most developing countries, demand management (the "soft path") is a necessary but insufficient condition for growth, development, and adaptation to climate change. Supply management and control of increased risks through reduction of a wide array of uncertainties is an essential adaptation mechanism. Pakistan suffered a devastating flood in 2010, while trying to feed a population that has increased from 34 million in 1950 to over 180 million in 2010. Or consider Bangladesh, whose population was 44 million in 1951, growing to 164 million in 2010. In 1988, Bangladesh suffered its most severe flooding, covering over 60% of the country, causing severe damage to thousands of miles of roads and embankments, with a loss of life estimated well over 100,000. Even if they improved all the agricultural water use efficiencies to the maximum possible extent, neither Pakistan nor Bangladesh would be able to feed their respective populations in the year 2050, nor protect them from the prospective increased floods and droughts associated with global warming with their existing water management infrastructure. Simply put, the "soft path" is wholly inadequate for the needs of most of the developing world, as the sole strategy for development, especially in the face of global warming and climate change.

In most cases, the extremes and changes we are experiencing are still within the "norms" of natural historical climate variability – albeit based on relatively short, century-long historical records. Our existing water resources infrastructure was designed to accommodate such variability. In the past, standard engineering practices accounted for those structural failure uncertainties by explicitly designing project redundancy for numerous features. Hence, "levee freeboard" was added to account for a "standard project flood," which itself was calculated to accommodate the uncertainties associated with hydrologic variability that is inherent in a relatively short hydrologic record. One could do away with these "safety factors," which compensated for a lack of information about climate variability, if one knew more about and could better predict future climate patterns. Unfortunately, the current generation of General Circulation Models (GCMs) cannot provide an adequate foundation for the design of hydraulic infrastructure such as dams, irrigation systems, levees, and culverts (Dessai and van der Sluijs, 2007; Dessai *et al.*, 2009). Hence, there must be a practical fall-back position that planners and designers can count on, in this interim period, as the water profession awaits improvements in GCM forecasting skill. These improvements, however, are not expected to materialize in the next two decades (WUCA, 2009).

Hence, from a purely practical standpoint, it is imperative to adapt and extend existing conventional methods and evaluation criteria that would serve the same objectives, without resorting to unproven GCMs and questionable downscaling techniques. Risk and reliability analysis has long been a staple of engineering structural design and water resources planning (e.g., Yen and Tung, 1993; Modarres *et al.*, 2009). Risk-based decision analysis, on the other hand, is directed more toward justifying new projects by evaluating the desired services and planned outcomes of a particular project. Planners want to ensure that the planned services of a particular project are available under a variety of uncertain scenarios. Society wants reliable water supply, flood control, hydroelectric power, clean drinking water, and recreational boating, while also protecting natural ecosystems and channelling growth and development along a sustainable path. It is the uncertainty of future circumstances (scenarios) that requires risk-based decision making. At the core of water project justification is a complex set of benefit-cost procedures and evaluation principles that attempt to reflect the balance between economic growth, improved social well-being, and environmental quality (USWRC "Principles and

Standards," 1973; USWRC "Principles and Guidelines," 1983). And at the core of benefit-cost procedures is a reliance on hydrologic frequency analysis.

CHARACTERISTICS OF CONTEMPORARY WATER MANAGEMENT

To address the issue of climate change uncertainty within the context of water resources decision making which is further embedded within the broader framework of integrated water resources management (IWRM), one must ask what is the nature of those decisions. In any given region or location, planners and designers have to determine a broad set of related planning (appropriate scale/size of a project that maximizes public services) and hydraulic design (structural safety) issues that are always dependent on the frequencies of hydrologic and precipitation phenomena. Among the numerous questions confronting planners are the following:

- How high should a levee be, and what is the risk to those living behind it?
- How to characterize and identify a 100-year floodplain?
- How to manage a reservoir to accommodate uncertain spring runoff?
- How much storage in a reservoir should be allocated to irrigation *vs.* other competing future needs?
- What is the "safe yield" of a municipal water supply system?
- How safe is the structure under extreme flood conditions? Seismic events?
- What happens downstream if a structure fails?
- How much will a flood warning system decrease the risk and uncertainty?
- How to size the spillway for a rare flood?
- How should our procedures on life-cycle infrastructure management and performance accommodate our evolving understanding of climate change?
- What flood/drought frequency distribution should be used in a particular analysis to accommodate climate uncertainty?

Water resources management is about transforming the destructive elements of nature (floods and droughts) into productive uses and values, such as ecosystem protection, water supply, and hydropower. It is about efficiently operating the existing infrastructure to provide a wide array of reliable services as population grows and expands and its needs change. It is also about planning and designing new infrastructure to deal with future anticipated needs and demands and increased risks associated with climate variability. The two aspects of management – the contemporary operational mode and the future strategic mode are linked, but require different evaluation and decision-making approaches, which treat climate uncertainty differently. In either case, water resources management is essentially bounded by how the extremes – floods and droughts – are defined and characterized, along with a diverse array of methods, evaluation procedures, and standards for reducing risks to society. Virtually all major infrastructure requires some estimate of what the extreme events have been historically, as the probabilistic basis for structural reliability analysis – that is, to ensure the hydraulic safety of a structure.

It should be recognized that water management systems are not designed to deliver services or protect against the full range of 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, while maximizing benefits. This benefit-risk-cost balance is constantly being adjusted by societies – either as new climate and hydrologic information comes in, or new urban and land use patterns create increased exposure to a larger set of environmental risks. That is why flood protection standards for flood and drought infrastructure reliability have evolved to a level of about a 100-year return period – they approximate that historically determined risk-cost optimum for our systems. The scale or appropriate "level of protection" or reliability of a project is the first consideration of an analysis – focusing on a balance between enhancing public safety, maximizing economic productivity, and reducing economic damages. The second consideration is the physical integrity of the structure – that is, the safety and reliability of the structure itself, which is a correlated aspect of engineering design.

For example, 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 floodplains to about a 500-year level of flood protection (Interagency Floodplain Management Review Committee, 1994). One can view this pragmatic response to flood risk uncertainty as increasing flood protection robustness and resiliency. However, societal decisions to change flood frequency analytical methods, or devise new norms for flood protection or benefit-cost procedures – usually go through a complex and lengthy process of approvals at all levels of government. As long as there is considerable controversy associated with the science of climate change and the utility of GCMs as the basis for analysis, U.S. federal agencies will find it difficult to promote alternative procedures – many of which add more uncertainty to an already complex evaluation framework.

Defining social risk tolerance and service reliability is part of a "social contract" that is determined through the political process coupled with public participation – a continuous "dialog" within each society – whether it be for new drugs, nuclear power plants, or water infrastructure. These norms are routinely adjusted, as part of a progressive adaptation to changing demographic trends and social needs. Every major flood and drought catalyzes a reevaluation of the accepted norms for risk tolerance, reflecting an inherent "autonomous adaptation," responding simultaneously to demography and nature.

Introducing "safety factors" into the design of water infrastructure was the equivalent of applying an early version of the "precautionary principle" (IPCC, 2001) to deal with the unknowns – that is, those aspects of hydrologic phenomena that went beyond conventional risk and uncertainty analysis, particularly in view of the longevity of such structures, and operating period.

Early engineers knew that there was persistence in the hydrologic record; that there were trends and multidecadal fluctuations, and understood that there were events that were much larger and more extensive than the short hydrologic records they typically dealt with. They planned for the unknowns by designing system redundancy and adding safety factors. Redundancy increased system robustness and resilience. 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 an ever expanding range of needs and conditions by sequential reallocation of storage and changes of operating rules. These original projects, designed under the old design standards, have been shown to have more resilience and robustness than anticipated (Fiering, 1982; Rogers and Fiering, 1986).

If water managers are to deal with climate change in a meaningful way – particularly for large water management infrastructure, a substantially different water management decision and evaluation 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" (RDM) – a process designed to accommodate uncertain scenarios, coupled with evaluation and project justification principles that focus less on optimal outcomes and more on "satisficing" – that is, producing robust solutions that may not meet strict economic efficiency tests, but are still risk cost-effective. The beginnings of a comparable conceptual process was laid out by Lempert *et al.* (2006) and explicated for climate adaptation by Dessai and van der Sluijs (2007).

ADAPTATION, ADAPTIVE MANAGEMENT AND VULNERABILITY ANALYSIS

For the past 50 years, the U.S. 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 and Stakhiv, 1998; Stakhiv, 1998). Autonomous adaptation (IPCC, 2001) has been defined as an *ad hoc*, incremental process that individuals, businesses, and governments use to deal with perceived risks, hazards, and vulnerabilities as they become apparent. For the U.S., this *ad hoc* adaptation, nevertheless, encompasses a continuous suite of policy innovations that have been systematically advocated and incorporated into legislation in a progression of congressionally authorized "Water Resources Development Acts," environmental protection legislation, and Executive Orders related to floodplain management, ecosystem management, and a host of other institutional and technological changes. Autonomous adaptation in the U.S. and the European Union has built on, and progressively incorporated many of the principles associated with IWRM, climate adaptation, adaptive management (AM), and sustainable development (Loucks *et al.*, 2000). These approaches, and associated changes in evaluation and normative decision rules for water resources management, comprise the conceptual foundations of an evolving pragmatic approach to dealing with climate change uncertainties.

Climate Adaptation

The water resources management sector has developed a variety of strategies to deal with periods of high demand and low water availability, consisting of longer term infrastructure "adaptation" to stationary climate signals and shorter term "adaptive management" measures that center mostly on flexible operations, forecasting and innovative uses of existing delivery and supply infrastructure to meet unexpected demands and ameliorate extremes of weather. There are essentially five ways that water managers have of adapting to climate variability and change, and different water management strategies employ various combinations of all the categories listed below:

- 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 reuse, recycling, solar energy).

When discussing practical decision-making methods for adaptation, it should be noted that there have been very few failures of the nation's water management infrastructure – that is, where the infrastructure failed before its design capacity was exceeded. The Mississippi River flood protection system worked as designed during the recent record floods of May, 2011. It should also be noted 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 through the 1970s – well before the era of sophisticated modeling, risk and reliability analysis and the existence of an adequate database for determining risk and uncertainty associated with climate variability. Yet, these structures stand and have performed effectively through a wide range of unanticipated climate variability – in other words they have been designed to be remarkably robust and resilient. This reality suggests that the current suite of methods, combined with the evolving changes in a more integrated institutional infrastructure (i.e., IWRM) can serve as an effective platform for climate adaptation (GWP, 2009).

Dessai and van der Sluijs (2007) recognize this reality, and have labeled this engineering and standards-based approach as the "bottom-up" approach. The characteristics of the "bottom-up" approach are that they are better able to deal with unknowns, ignorance, surprises, and uncertain information. Dessai and van der Sluijs recognized that the "top-down" approach, based on GCMs is too fraught with a cascade of uncertainties and assumptions related to greenhouse gases, imperfect climate modeling algorithms, and uncertain, perhaps unknowable, future scenarios. GCMs have been shown to be unable to adequately replicate the past 30 years of historical climate (Stainforth *et al.*, 2007; Koutsoyiannis *et al.*, 2008; Anagnostopoulos *et al.*, 2010; Trenberth, 2010). However, there are specific changes that could be made to strengthen the existing practical suite of mechanisms for improved adaptation to climate uncertainty.

Water resources management, which has evolved with its core principles of climate adaptation and AM, 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, multiobjective 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 prerequisite for any strategy that intends to effectively deal with climate change adaptation (GWP, 2009, 2010). One cannot imagine a successful climate adaptation strategy without a well-functioning institutional management platform. IWRM is the management framework for achieving sustainable development (Stakhiv, 2003). Improved governance, through IWRM is the principal means for resolving competition among multisectoral demands on a fixed water resources base. Each water-dependent sector (environment, water supply, sanitation, agriculture, hydropower, navigation) fashions its own set of management principles, rules and incentives that are maximized, and often in conflict with one another. Resolving those inherent, intersectoral institutional conflicts is as important for successful climate adaptation as realigning the multiobjective basis for project justification.

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" (National Research Council, 2004). It 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. Adaptive management is perfectly suited for many of the short-term 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, particularly in developing nations, by reducing the vulnerabilities of existing systems, improving productivity and water use efficiency, and reducing flood damage losses.

One of the key principles of AM is that policies and projects be designed so that they provide for continuing resource production while simultaneously probing for better understanding. In other words, create a monitoring and evaluation system that tests the performance (reliability, robustness, resilience) of a plan or project under a variety of plausible conditions and assumptions. Also, conduct periodic "stress tests" and exercises, simulating new information and response strategies. These "stress tests" are the equivalent of GCM-based vulnerability analyses – except that they are undertaken on existing projects, with a more plausible set of scenarios, and performed periodically, as part of a contingency planning performance review. Vulnerability assessments on the existing infrastructure are an inherent, fundamental function of AM.

There are many 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. Figure 1 shows the Corps of Engineers' various operating procedures and manuals that are related to reservoir management that should be routinely revised and adapted as new information becomes available and the need arises for such revisions. Climate change adaptation will require a proactive and systematic review and revision of the various manuals at each of the Corps' reservoir sites – but they cannot be undertaken routinely without adequate funding. Instead, as with most autonomous adaptation, these manuals are usually updated in the aftermath of a destructive flood or drought.

Vulnerability Assessment

In principle, vulnerability assessments can be useful, and have become the fashionable core of climate change impact analysis, with the ultimate aim of leading to an adaptation and AM strategy for water management. There is a practical discontinuity in such an approach because vulnerability assessments are usually linked with GCM predictions and questionable downscaling methods for precipitation and conversion to runoff. Dessai and van der Sluijs (2007) consider vulnerability assessments that begin with GCMs as the "top down" approach. They downplay this approach because of our inability to realistically deal with the cascading uncertainties inherent in the GCMs and downscaling methods and explicitly account for these uncertainties in the subsequent detailed evaluation requirements for project justification. For example, recent work by Angel and Kunkel (2010), focusing on the Great Lakes system, tested 565 scenarios generated by 23 GCMs. They demonstrated that the variability and uncertainty of any single GCM depended on the starting boundary conditions, resulting in a wide array of highly variable outcomes (lake levels) for any selected GCM. Even with the assistance of robust decision-making procedures (Lempert *et al.*, 2006) it is not clear at all, how these scenarios can be effectively used for any sort of meaningful evaluation or vulnerability assessments, especially for designing water management projects or operating rules.

The point is that AM is a continuous process of vulnerability assessment, which includes monitoring and feedback, and is considered to be a superior and more practical substitute for the more static GCM-based assessment that relies on information which is biased and highly uncertain. Vulnerability assessments, performed via "stress tests" on operating systems should attempt to quantify the performance of the system under a variety of conditions, using a common set of performance metrics devised by Hashimoto *et al.* (1982), to account for risk and uncertainty inherent in water resources system performance evaluation. These metrics include quantitative measures of reliability, robustness, resiliency, vulnerability, and brittleness.

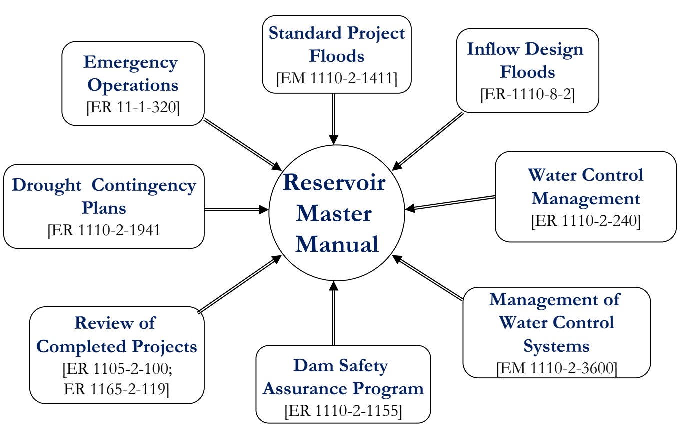

FIGURE 1. Corps Reservoir Operations Manuals.

WATER RESOURCES DECISION MAKING

A distinction is made between water *management* – that is, implementing a set of policies and operating systems in conformance with those policies – and public *decision making* for developing new policies that underlie justification of new projects, new programs, and regulations. What constitutes conventional water sector decision making? First, one must understand that all water management decisions, including the development of design criteria for hydraulic structures, are made within a much broader socio political and institutional context. Decision-making protocols and evaluation criteria are constantly adjusted to reflect shifting societal perspectives on the proper roles of the public *vs.* private sectors. These perspectives evolve through a continuous series of policy adjustments and feedback that serves to define the specific societal goals and objectives – whether for environmental protection, floodplain restoration, economic development, sustainable development, social justice, or social welfare. Policy initiatives are transformed into legislative initiatives, which then "trickle down" through a series of regulatory, administrative, organizational, and procedural changes – all of which are subsumed under the rubric of "institutional changes." The basic decision criteria and evaluation principles that are currently used for project analysis are the essential determinants of whether a project can be justified to accommodate future climate variability. It is these decision criteria that comprise the essence of decision making, and which are most problematic for climate adaptation.

Hydrologic Analysis for Project Justification

Every method that is currently used is based, at least partly, on risk-based procedures – that is, requiring some knowledge of probabilities and uncertainties of the key variables and parameters associated with the fundamental decisions to be made about project design. Flood and drought frequency analysis is at the core of project-based risk and reliability analysis. There are two basic ways that water engineers have of establishing flood or drought risk, which is the basis of a framework for establishing project justification and design. One approach is probabilistic, based on the statistical properties of an observed sequence of hydrometeorological events. The other is largely deterministic, based on the same rainfall events, combined with physical runoff factors and assumptions that are designed to create a sequence of worst case scenarios. For most hydraulic design factors that dealt with structural integrity, design standards were largely based on deterministically derived worst case scenario events, such as "standard project flood" or the "probable maximum flood." Probabilistic hydrologic frequency analysis consists of fitting a selected probability distribution to a record of observed events. However, there is no specific or inherently obvious or unique probability distribution for selected hydrologic phenomena, though the community of hydrologists has spent decades converging on a few basic principles.

The current framework for probabilistic analysis that has been developed over the past 25 years in the U.S. are to be found in the "Guidelines for Determining Flood Flow Frequency," commonly known as Bulletin 17-B (IACWD, 1982). This methodology has been refined further by the USACE (1996) to include a Monte Carlo simulation approach to explicitly factor in all the uncertainties associated with stage-discharge and stage-damage computations that underlie project justification. Flood frequency analysis is linked to socially determined norms for floodplain management, flood insurance rates, and the relative degree of risk avoidance for which a society is willing to pay. Most required hydrologic analysis serves the needs of benefit-cost analysis that serves as the underpinnings and rationale for justifying a prospective water management measure/action. If so, what is the optimal size/design and what are the most economically efficient purposes (services) that should be provided? The secondary, and mostly engineering purposes of hydrologic frequency analyses are to determine under what hydrologic conditions the designed infrastructure might fail, that is, hydraulic reliability, and to ensure that the hydraulic structure is designed and constructed in a manner as to be able to withstand a selected design event, together with a "reasonable/plausible" range of uncertainty.

Traditional flood frequency analysis employs a standard set of "stationary climate" assumptions. Necessary assumptions for a statistical analysis are that the array of flood information is a reliable and representative time sample of random homogeneous events; that the annual maximum peak floods are considered to be a sample of random, independent and identically distributed (i.i.d.) events; and it is assumed that climatic trends or cycles do not affect the distribution of flood flows in any important way. Global warming brings into doubt the assumption of climate stationarity, since future climate may be different than the recent past (Milly *et al.*, 2008). But, there is no straightforward or acceptable way of deriving flood frequencies from current GCM-generated precipitation data (Stainforth *et al.*, 2007; Koutsoyiannis *et al.*, 2009). On the other hand, there are methods that are routinely being used by federal water management agencies which deal with risk and uncertainty analysis of existing hydrologic data, that could be extended, somewhat, in dealing with climate uncertainties (USACE, 1996; Brekke *et al.*, 2009). Different types of frequency distributions can be applied as part of sensitivity tests, using Monte Carlo simulation techniques, to determine how the uncertainties of extreme events affects the economic viability and the technical feasibility of alternative designs – the equivalent of a robustness and reliability analysis.

Fundamentally, for practitioners, the intricacies and uncertainties of climate change and climate variability have to be condensed into an examination of the tails of a frequency distribution. As Hirsch (2011) has noted:

The changing means may be interesting, but what matters most to design or operations are changes in the behavior of the tails. Thus, in the world of predictive models and in a world of statistical analysis, we have the most confidence in statements about the least important aspects of hydrology, and the least confidence in the most important aspects.

That is why there is so much debate about flood frequency analysis, and whether the properties of a particular probability distribution like Log-Pearson III (LP3), can accommodate nonstationary climate change. The recent "Workshop on Non-stationarity, Hydrologic Frequency Analysis, and Water Management" (Olsen *et al.*, 2010), dwelled on alternatives to the LP3 formulation and noted that there has been an ongoing decadal effort to update and expand the utility of LP3. Noteworthy was the fact that there was no clear agreement on whether "stationarity" was "dead" (Milly *et al.*, 2008). In fact, there was quite a bit of discussion among the invited speakers that the proposition that "stationarity was dead" could neither be supported by the theory (Koutsoyiannis, 2011; Lins and Cohn, 2011), nor by the data (Villarini *et al.*, 2011). In a reanalysis of Mississippi River flood frequencies, after a series of record floods, Olsen *et al.* (1999) found that the LP3 formulation was still valid and useful, based on the updated historic series, but could not deal effectively with trends that had become apparent in the record. Whether these trends were part of persistent cycles or emerging climate change signal, could not be determined.

The problem of modeling extreme or rare events arises in many areas where such events can have very adverse consequences. Extreme floods and droughts are generally underestimated by normal or LP3 distributions. To develop appropriate probabilistic models and assess the risks caused by these events, water resources engineers frequently use the extreme value distributions. The generalized extreme value (GEV) distribution is the limit distribution of properly normalized maxima of a sequence of independent and identically distributed random variables. Because of this, the GEV distribution is used as an approximation to model the maxima of long (finite) sequences of random variables (Coles, 2001). Japan and several European countries use GEV for their flood frequency analysis. It is important to correctly account for extreme events in any economic evaluation, especially with an uncertain evolving climate change future. The GEV is considered a "fat-tailed" distribution because it inherently gives more weight to extreme events.

An example that demonstrates these "fat-tailed" properties is a comparison of the LP3 distribution and a GEV distribution that is fit to the same series of hydrologic data – annual flood peaks of a river. Figure 2 shows that a flood which is estimated to have a 100-year return period by the LP3 distribution, has only a 45-year return period using a GEV distribution. This property would make justifying a local flood control project much easier for that particular community because it does not discount the low probability (i.e., 100-year) event as much as the LP3 distribution. The choice of a probability distribution for analysis is relatively arbitrary, as is the relative degree of protection for a community. However, the choice of a particular distribution, when coupled with a high economic discount rate, can greatly affect the choice of how a community adapts to flood risks, by eliminating a wide range of structural solutions, and reducing the reliability and robustness of a selected plan. The properties of the GEV distribution are such that it is more compatible in dealing with the increased uncertainties inherent in climate change, especially for extreme conditions, and should be considered for future project justification procedures (Rajagopalan, 2010).

Multiobjective Planning

The science of hydrology, hydraulic engineering, watershed modeling, and data collection has improved dramatically since the 1970s, especially with the advent of satellite-based data and advanced computational methods. However, the dominant changes that influence the design of contemporary water resources management and delivery systems since 1970, have come from the multiobjective planning paradigm, rather than changes in engineering design standards and criteria. The basic standards used for designing hydraulic infrastructure are based on hundreds, if not thousands of years of engineering experience and empirical analysis. Planning and evaluation principles, on the other hand – those that are

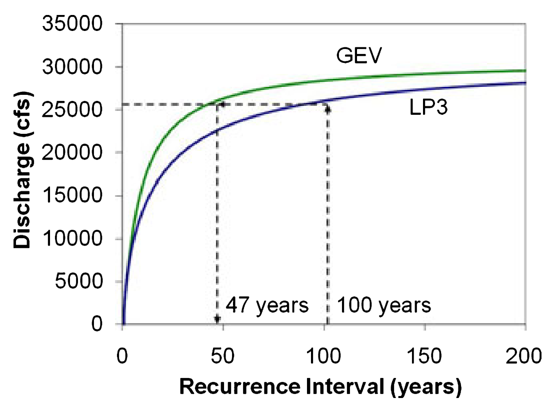

FIGURE 2. Comparison of GEV and LP3 Probability Distributions for Flood Frequency Analysis.

used to justify the social, economic, and environmental purposes – have changed dramatically during the past 50 years, influenced largely by the ideas of the Harvard water program (Maass *et al.*, 1962). The principal purpose of planning, under the revised paradigm, was not to design reliable, robust and resilient hydraulic structures, but to design projects, programs and water delivery systems that served a more diverse range of social needs, while adequately accounting for the direct and indirect economic, social and environmental benefits and costs, and optimizing net economic benefits. These were the principles that underpin our modern concepts of sustainable development, as reflected in the U.S. Water Resources Council's "Principles and Standards" (USWRC, 1973).

The addition of numerous other social, cultural, esthetic values, ecological requirements, along with a host of new project purposes that were never explicitly authorized by the original project legislation (e.g., recreation, ecological flows, floodplain benefits, etc.), all served to reduce 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, sustainable development principles that progressively have been superimposed onto existing projects, 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." Equally, the focus on risk and uncertainty analysis, together with economic optimization, effectively reduced much of the engineered redundancy of many projects that were based on the original deterministic standards-based paradigm. Over time, the existing portfolio of projects will have a progressively reduced ability to deal with increased climate uncertainties. Applying the principles of RDM would counteract some of the current tendency of economic optimization procedures that generate "brittle solutions."

However, the dilemma is that implementation of sustainable development principles requires a multiobjective problem formulation and associated evaluation framework, akin to the original national planning objectives contained within the "Principles and Standards" (P&S) guidelines for water resources planning and evaluation of the USWRC (1973). This P&S framework, which is no longer in use, is comparable to the one proposed by President Clinton's Council on Sustainable Development (PCSD, 1996) which recommended a set of national planning goals for sustainable development that are very comparable to those of the P&S (Loucks *et al.*, 2000). The four original principal goals for achieving sustainable development consisted of economic prosperity, environmental health, social well-being, and equity. However, the current family of project evaluation methods employed by the water sector, which are primarily based on an emphasis on economic efficiency, cannot effectively deal with climate change uncertainty, and would be especially problematic in contending with the suite of anticipated adverse environmental consequences associated with global warming (Stakhiv and Major, 1997).

The evolving paradigm of "RDM," adopted from Lempert *et al.* (2006), is a starting point for dealing with multiple climate scenarios and uncertainty. It must be embedded in the original P&S multiobjective evaluation and project justification framework used by federal water agencies that incorporates the principles of the PCSD. These include a refinement of the original federal multiobjective planning and evaluation objectives that includes National Economic Development (NED), Environmental Quality (EQ), Regional Economic Development (RED), and Social Well-Being (SWB) as co-equal federal objectives (Major, 1977). Again, these ideas are not new and the strategy needed is essentially a "return to the future," that is, reconstituting and rearranging old ideas that were not capable of being effectively implemented at that time, and fashioned into a more practical, updated framework that would deal with the uncertainties, unknowns, and surprises that might be associated with climate change – both for operating water infrastructure and for new projects. The reconstituted planning and evaluation framework, must be coupled with changes to economic decision rules and protocols, complemented by a new family of risk-based engineering standards. Those are the three quoins of a modified paradigm for "RDM" that would support the design of a new family of climate adaptation projects.

Economic Project Justification Criteria

Water management is about providing public services, and our evaluation methods and criteria, which are designed to direct those services to the highest public needs, dominate the decision processes. The design of new water infrastructure projects presents the biggest challenge in the current circumstances, that is, during the transition period, as the life of a typical water management project is usually 50 years or more, and encompasses the period when climate change impacts are expected to become more evident. While standard hydrologic methods provide necessary inputs into the evaluation framework, it is the economic decision criteria and evaluation practices that most require revision to be compatible with increased uncertainty. For example, the choice of the discount rate in any economic analysis, whether it be the internal rate of return or classical benefit-cost analysis, is the single most important determinant of the economic viability of a water project (Lind, 1997; Rogers, 1997). It is difficult to economically justify a project that is supposed to encompass future but highly uncertain increased climate variability expected to materialize in 2050, when a discount rate of 7 or 8% only effectively accounts for a benefit stream of a particular dam or irrigation system for 15-20 years hence. A discount rate of 3%, which is normally viewed as close to the "social rate of discount" (Lind, 1997), stretches the planning horizon, that is, the period over which significant benefits are generated to approximately 45-50 years, which is the conventional life of major water infrastructure. A discount rate of 10% narrows the planning horizon to 12 years. So, under current economic justification procedures, the largest climate-related impacts, in the form of increased hydrologic variability (larger floods and droughts) that might be expected to become more evident 30-40 years from now, would not play a significant role in providing an adequate economic justification for a long-lived hydraulic project that is designed today for potential adaptation to a future uncertain climate.

In fact, there is a "quadruple discount dilemma" at play in contemporary water project justification which is incompatible with the search for "no regrets" climate adaptation solutions, greatly constraining any substantive adaptation via major hydraulic structures to deal with future climate changes. All four mechanisms serve to sequentially discount the effects of uncertain, low probability–high consequence events, such as extreme floods and droughts, and hence, to greatly constrain the economic justification of water projects that span more than 50 years. The first is the use of the LP3 *probability distribution* which diminishes the importance of low probability events, in comparison to a "fat-tailed" GEV distribution. The second is the *economic discount rate* that is currently used for economic justification, which is considered to be too high for dealing with adaptation mechanisms for intergenerational phenomena such as climate change. The third form of discounting, which amplifies the effect of a high discount rate, is the traditional use of "*expected annual damages*" (or expected value – EV) formulation for determining the EV of damages over the life of a project. This analytical formulation relies on summing up the product of the frequency of an event and the associated discounted benefits or damages. This approach inherently discounts the large economic impacts of low probability–high damage events such as extreme floods and droughts. If one is to accept the results of some GCM predictions – that is, that hydrologic variability will increase with global warming, then the EV basis for economic justification of increased capacity of future water projects cannot adequately account for this projected increased variability.

The fourth factor of the "quadruple discount dilemma" that underlies contemporary project justification procedures, is the fundamental optimization decision criterion which requires the selection of a project scale or size (e.g., levee height, navigation channel depths, reservoir storage volume) which "*maximizes net discounted benefits*." The regulations are clear:

> The alternative plan with the greatest net economic benefit consistent with protecting the Nation's environment (the NED plan) is to be selected unless the Secretary of a department … grants an exception when there are some overriding reasons for selecting another plan … (USWRC Principles and Guidelines (1983), Chapter I, Section X, Plan Selection)

This means that for federally subsidized water projects, there is a federal objective and plan selection rule that imposes a "national economic efficiency" standard for federal participation in water resources projects. Planners are directed to formulate plans for relevant project purposes (e.g., navigation channels, flood control, hydropower, or water supply) and to recommend, for federal investment, the plan that maximizes the difference between money measures of aggregate benefits and costs, as calculated by summing measured economic gains and losses realized by affected individuals (Scodari, 2009). Collectively, these four decision rules and methods that underlie project justification, would greatly impede the economic justification of a robust water project designed to deal with future increased climate variability and uncertainty.

Haimes (2004) makes a comparable case in his treatise on risk analytic methods regarding the routine application of EV to problems of low probability-high consequence events, like nuclear power plant failures or dam safety issues. To remedy the bias inherent in EV, Asbeck and Haimes (1984) developed the partitioned multiobjective risk method (PMRM) which recognizes that damages fall into frequency-based domains, and that catastrophic damages of low probability events should be given greater weight in the evaluation process, depending on a series of factors such as population at risk and the relative effectiveness of flood warning and evacuation systems. The PMRM focuses on how important the tails (extremes) of a probability distribution are to a decision, and the consequences of failure in each partitioned domain. The PMRM generates a number of conditional expected-value functions, termed "risk functions" that represent the risk given that the damage falls within specific ranges of the probability distribution. This partitioning of probability domains allows one to more closely examine the relative effect of failure and consequence, and allows a decision maker to weight the relative importance of each domain to better reflect the conditional expectation of adverse consequences.

ADOPTING A NEW PARADIGM FOR DECISION MAKING

To more effectively accommodate the new version of the RDM, together with the broader aims of sustainable development, there will have to be a paradigm shift from the deterministic, economic efficiency centered view embodied in the "Principles and Guidelines" (USWRC, 1983), based on a view of a relatively stationary climate, to a much more flexible set of multiobjective 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. The reconstituted planning and evaluation framework, must be coupled with changes to economic decision rules and protocols, along with a return to risk-based engineering standards. Those are the three quoins of a modified paradigm for "RDM." Fundamental changes must come in the economic evaluation principles that are used for project justification. This could ultimately mean changing the basic decision rules from "maximize net benefits" to "minimize risk cost," or something more akin to "maximize risk-cost effectiveness."

There are many improvements in existing conventional approaches that can be made, which fall under the general rubric of "RDM." The original concept of 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, without resorting to strict economic decision rules for selecting an "optimal" project or course of action. 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.*, 2006).

A variant of this strategy has been evolving in the water management community for the past few decades. For example, Rogers and Fiering (1986) noted, in an evaluation of how systems analysis and optimization models were being employed by the U.S. 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 that were not being considered as part of planning. 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 evolved in the Corps of Engineers and applied successfully under the label of "Shared Vision Planning" (Werick and 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, 2006) and the International Upper Great Lakes (IUGLS, 2009; Brown *et al.*, 2011).

PRACTICAL RECOMMENDATIONS

Since climate change, like drought, is a "creeping," slowly evolving uncertain phenomenon, it will not serve to catalyze actions in a politicized world that has profound difficulties in dealing with highly uncertain actions and programs that require huge investments upfront to avoid unknown risks. There are several levels of practical steps that could be taken as part of an overall pragmatic strategy to deal with the uncertainties of future climate change. The first level is an *intra-agency strategy* – one that any agency, such as the Corps of Engineers or Bureau of Reclamation, can initiate as part of their own set of discretionary actions, within the authorities they possess. The second level is more of an *interagency science coordination* initiative that would address the issue of a new family of hydrologic techniques for risk, reliability, and uncertainty analysis that could be used for emerging aspects of climate uncertainty. This would include the development of probability distributions which are compatible with the uncertainties of climate change – that is, "fat-tailed" probability distributions which inherently give more weight to the uncertainties of hydrologic extremes. This interagency coordination is already underway (Brekke *et al.*, 2009). Finally, the third level of engagement would be policy driven, and deal with changing the basic decision rules and evaluation procedures and criteria – such as employing a social discount rate for long-lived publicly financed water projects; methods for determining expected annual damages; and associated optimization decision rules such as "maximize net benefits" or "minimize risk cost" that need to be revised for compatibility with the nature of risks and uncertainties posed by climate change. This could best be accomplished through a mechanism equivalent to the old Harvard Water Program (Maass *et al.*, 1962), or a special independent Presidential Commission or a reconstituted U.S. Water Resources Council. This policy-driven engagement has not begun, as yet.

An example of the first level of intra-agency initiatives is from the USACEs' Secretary of the Army Congressional Testimony (2007). It 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 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 existing water infrastructure ("stress tests") under varying scenarios.
- Increased inspections, oversight and regulation of infrastructure during operation and maintenance.
- Increased research and development oriented toward 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 problem of practical adaptation to the uncertainties of climate change must be attacked from various directions and at different levels of engagement – from legislative changes in Congress to analytical procedures at each agency. The GCMs cannot provide the quality of information required for adaptation over the next two decades. That is why AM exists as a viable tool – to explicitly deal with uncertainties as part of operational management. Agencies cannot rely on information derived from the cascading uncertainties inherent in GCMs to either plan new projects nor for operating existing ones. An alternative, practical interim approach has been suggested, while climate science continues to improve. The basic elements of a pragmatic approach that would serve to carry water management planning and design through the interim period of the next two decades consists of:

- A revised set of evaluation procedures for a "RDM framework."
- A uniformly developed set of risk-based engineering design standards for hydraulic structures.
- Applying of a "social rate of discount" for project justification.
- Application of GEV probability distribution (or equivalent) in place of LP3 for flood and drought frequency analysis.
- Discarding EV as basis for damage estimation and replace with a "risk-partitioning" formulation that explicitly accounts for low probability-high consequence events.
- Upgrading IWRM as the framework for implementing climate adaptation and AM measures.
- Focusing on AM elements of forecasting, monitoring, "stress tests," and contingency planning for existing water infrastructure systems.

A process has already begun in many federal agencies to deal with the uncertainties associated with climate change uncertainty. For example, Executive Order 13514, "*Federal Leadership in Environmental, Energy, and Economic Performance*" (2010), requires the establishment of climate change adaptation planning procedures by each federal agency, along with an action plan by June 2012. However, this process does not address the basic changes that are needed for a new family of decision rules for project justification.

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