International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

Methods and Tools to Manage Water Resources for an Uncertain Future

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ABSTRACT: In the face of growing demand and uncertain supply, there is an increasing necessity for creative management policies better suited to contemporary water resource dilemmas. Model simulation is a powerful tool that can enhance decision-making and management activities. Modeling can provide a bridge between science and policy through conceptual models; which are the basis for communication between managers and scientists. Uncertainty is another concept of importance in bridging that gap so as to improve current management practices. To make the modeling applications of active decision-making relevant, different forms of uncertainty related to model simulations need to be explored and understood. In hydrologic applications, a key requirement in the effective management of water resources is a mechanism for efficient allocation of water among competitive uses that maintains a system of checks and balances to prevent excessive and irreversible damage to the environment. One such mechanism is the use of regional water markets to help in the redistribution of water between different demand sectors. The Universities of Arizona, and New Mexico, are collaborating in the development of models used to simulate and examine several water property trade factors, including water right priorities, third party effects, and the spatio-temporal availability of water. To complement the study of present-day implications of water leasing, potential future implications of water markets under alternative and uncertain evolving future regional scenarios are being examined. Such use of scenarios enables the systematic study of different components of a complex system.

INTRODUCTION

Increasing resource scarcity that continues to stress existing water systems has generated growing concerns over the sustainability of global and regional water supplies. As water demand expands and the state of water supplies becomes more uncertain, the need for creative and improved water management practices and policies becomes very critical. Water resources managers and decision-makers are regularly forced to make crucial decisions under highly complex and uncertain circumstances (Liu *et al.*, 2007a, Gupta *et al.*, 2007).

Enhancing water management applications requires current management practices and techniques to directly correspond to contemporary water resource issues. Science has been compelled to provide information for complicated environmental decision-making processes. Such scientific information must be relevant, accessible, understandable, acceptable, and compatible to stakeholders and decision-makers (Liu *et al.*, 2007a). To achieve this goal, innovative science must be intimately connected to active decision-making. Great demand for effective integration between science and decision-making coupled with the necessary obligation of science informing management

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decisions renders the improvement of the integration interface to be a high priority. This integration can beneficially influence management decisions adopted by water managers and stakeholders.

The primary way of facilitating integration is through the utilization of methods and tools that can assist in infusing science into decision-making (Gupta *et al.*, 2007). Strategies and tools that help integrate science with decision-making can examine the implications of potential water-related decisions prior to implementation and thus provide useful input towards achieving optimal water management practices. This paper discusses some of these integration tools and strategies; including model conceptualization and simulation, issues of uncertainty, communication, and scenarios.

MODEL SIMULATION

Integrated numerical modeling has been recognized as a necessary strategy to support water resources systems decision-making by modeling key interactions between natural and human systems. Model simulation can explore various decision options as it can produce multi-resolution results that are also multi-disciplinary (Gupta *et al.*, 2007). By integrating science's best knowledge and data, models can become useful instruments of prediction. As devices for communicating scientific knowledge, modeling propels the widespread adoption of science into resource management (Beck, 2007).

An essential role for modeling is to tackle system complexity by incorporating it into models. Models provide a methodical mechanism that assembles information from numerous domains in order to connect multiple assumptions and hypotheses regarding a system's behavior (Parsons, 1995). The advantages of assimilating modeling into resource management decision-making includes; flexibility in exploring options, robust analyses, internal consistency, knowledge transferability, and the ability to conduct sensitivity and uncertainty analyses (Hisschemoeller *et al*., 2001). Effective approaches utilize models that inherently have the characteristics of aptitude transparency, computational efficiency, and user-friendly interfacing for the examination of stakeholder-driven issues.

One major limitation in applying model simulations to planning and management activities is the difficulty of incorporating certain types of system behavior (e.g. social and institutional) into the model structure with realistic accuracy. This limitation contributes to the issue of trade-off between understandability and credibility when it comes to model complexity. Stakeholders can understand the model only if model complexity is at a level they can comprehend (understandability), however the modeled representation of the system must be sufficiently realistic (complex) for stakeholders to accept the validity of the results.

CONCEPTUAL MODEL

A conceptual model is a simplified description of the numerical model to be developed based on the real system. The conceptual model describes and represents the assumptions, hypotheses, simplifications, principals, themes, content, input, outputs, variables, parameters, components, and uncertainties of the actual system's numerical model (Liu *et al.*, 2007b).

Conceptual models support modeling activities by explicitly capturing the essential relationships and dynamics of the mental reference behind a numerical model. It ensures that real situations are modeled accordingly and realistically. Conceptual models also enable us to understand computational and scientific models better and they provide the central basis of communication and dialogue to link a computational model with decision-support.

Beneficial conceptual models enhance understanding and credibility by bridging science and policy. They facilitate communication between decision-makers and scientists by bringing to focus the interactions of physical, environmental, social, hydrologic, and institutional dimensions. As a communicative "liaison", it also allows the easy incorporation of stakeholder input and feedback for the purpose of model validation and verification.

Creating a comprehensive conceptual model requires several traits to be inherent. The conceptual model needs to be complex at a level both credible and understandable to decision-makers; therefore the model's communicative ability and depth of physical knowledge needs to balanced. The conceptual model should clearly describe components, processes, temporal/ spatial resolutions, assumptions, limitations, and uncertainties. It must also consider a variety of factors and/or dimensions; e.g. water, human, natural, social, economic, etc. (Gupta *et al.*, 2007). An example of a conceptual model that incorporates various systems, variables, and connections is shown in Figure 1.

COMMUNICATION

Communication between scientists and decision-makers in modeling activities is essential for the augmentation of water resource management through

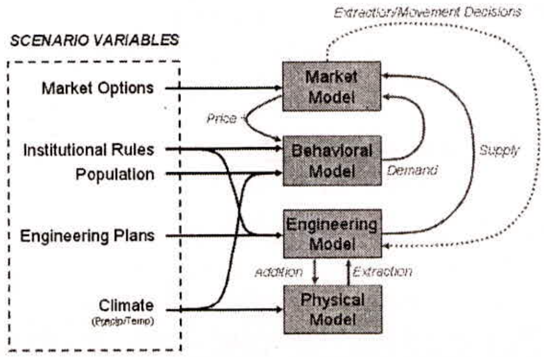

Fig. 1: Example Conceptual Model (adapted from NSF STC Center—SAHRA)

model simulations. All areas of policy have recognized the importance of better communication between scientists and decision-makers in general. This is even more prevalent in science integration efforts since stakeholder issues that are tied to science applications guarantee the adoption of scientific results (Liu *et al.*, 2007a).

Improved communication in this light has been hindered due to several prevalent reasons. A considerable disconnect exists between science and policy due to a difference of purposes, interests, concerns, and objectives between the two that ultimately leads to a lack of understanding for each other's systems (Lee, 1993; Jacobs, 2002; Sarawitz and Pielke, 2007). This disconnect has hindered the full exchange of information between the disciplines of knowledge and practice, as a result scientist input has been frequently ignored in decision-making and the scientific information prepared for decision-makers is often neither easily accessible, available, or usable (Acreman, 2005; Cash *et al.*, 2003; NSC, 1999). Additionally, from a manager perspective scientific research is often viewed as inexplicit in terms of clarity and comprehensiveness (McNie, 2007).

There exist a few solutions to tackle this communication problem. The adoption of a conceptual model as a communication tool can assist in facilitating constructive discourse. Decision-makers, stakeholders, and managers should be continuously engaged directly regarding scientific topics relevant to their work. With the aid of a conceptual model as a primary conversation piece during engagement, scientists can then attempt to produce usable results from a decision-maker standpoint.

UNCERTAINTY

Uncertainty, an intrinsic trait in aspects of modeling, can be defined as the inability to determine and predict the true response of a system. Uncertainty is important in model simulations since it poses a potential barrier to the effectual linking of science and decision-making. A better comprehension of uncertainties is integral for long-term planning in resource management. The issue of quantifying uncertainties is conducive towards establishing the highest degrees of confidence possible in making management decisions. As discussed by Mahmoud *et al.* (2007), uncertainty types in modeling include stochastic uncertainty, communication uncertainty, conceptual uncertainty, and future uncertainty.

Stochastic uncertainty is uncertainty resulting from numerical models. Approximations, estimation methods, and relationship functions can contribute to this type of uncertainty. How the model structure simulates actual conditions through formulas and empirical calculations can be a source of stochastic uncertainty. This is more evident in models with no model calibration or verification methods attached to them. Additionally, parameter sets and data linked with the numerical model have some uncertainty associated with them, especially if those data have been manipulated from their original form.

Communication uncertainty and conceptual uncertainty are related to conceptual models and are attributed to an incompleteness of knowledge. Communication uncertainty deals with the issue of communication between scientists and decision-makers using a conceptual model and how estimated uncertainty is communicated to decision-makers for their management purposes. In communicating uncertainty, transparency and clarity of the perceived uncertainties helps maintain credibility and trust in utilizing modeling for decision management.

Conceptual uncertainty is directly linked with how a conceptual model is formed. Perceptions regarding the system structure to be modeled can contain high subjectivity depending on the persons building the conceptual model. In creating the conceptual model, faulty assumptions, unskillful subjective judgment, ambiguity in definitions, and improper projections of system behavior increase the levels of uncertainty in the model. Consulting with experts on ambiguous ideas in conceptual model construction (e.g. behavioral relations) can lesson uncertainty produced from such areas. As a conceptual model gets refined and adjusted through communication between scientists and stakeholders, different agendas and priorities may induce some bias that compounds the uncertainty problem.

Future uncertainty arises in the application of scenarios and scenario models, which are discussed in the next section. This form of uncertainty comes from model simulations that are projected into the future. Future uncertainty is attributable to the processes behind the conceptual and numerical mechanisms that aim to propagate different trajectories of change into the future.

SCENARIOS

Scenarios are plausible descriptions of possible and potential alternative future states and outcomes. Scenarios are neither forecasts nor predictions since they do not aim to exclusively project the most likely future. The strength of a scenario lies in its ability to consider unlikely futures that have high impacts—an ideal characteristic for long-term strategic planning. Scenarios utilize implicit and explicit assumptions to describe simultaneous and dynamic variations to a system. By taking into account the relationships between system components and their trajectories of change, scenarios can identify impacts, risks and, opportunities (Liu *et al.*, 2007c; Wagener *et al.*, 2006).

Simulation models enhance scenario planning by simulating alternative futures quantitatively. Connecting scenarios to models requires the selection of appropriate models that can handle the type of variables and changes described in a scenario (Mahmoud *et al.*, 2007). Qualitative scenarios that are coupled with models take the form of numerical datasets. These scenario datasets are treated as inputs into the computational models; with each set of inputs describing scenario changes to key variable drivers of change of a system. Producing numerical results from modeling scenarios allows scientists to flesh out relationships, follow system interactions through time, and compare different strategies (Paich and Hinton, 1998).

Scenario studies add an innovative element to strategic long-term planning missing from decision-making and resource management. The thought process behind using scenarios is not unfamiliar to decision-makers who continuously plan for an uncertain future using alternative strategies. However, scenarios simulated using models in the dynamic manner described are still relatively new to the environmental management field. Scenario planning is most valuable when integrated into decision-making (Fahey and Randall, 1998). Since stakeholder input is critical to constructing scenarios of any value to water management, scenarios can reflect significant and predominant issues (Liu *et al.*, 2007c). Scenarios therefore help decision-makers plan for an uncertain future by incorporating human and science dimensions into policy making and exploring the implications of different management strategies. In this manner, the significant impacts of plausible alternative futures can be integrated into ongoing policy and management decisions.

APPLICATION EXAMPLE: WATER-LEASING MARKETS

A key requirement in the effective management of water resources is a mechanism for efficient allocation of water among competitive uses, while maintaining a system of checks and balances to prevent excessive and irreversible damage to the environment. One possible mechanism is the use of regional water markets to help in the redistribution of water between different demand sectors (e.g. agriculture, industry, municipal, environmental, etc.).

In the US Southwest, water-leasing markets have been considered as a tool that can circumvent water scarcity disputes through mutually economic water allocation (Gupta *et al.*, 2007). For the purpose of examining the types of human and environmental conditions that can support water markets, models are being adapted to simulate and examine several water property trade factors; including water right priorities, third party effects, alternative rule sets, and the spatial and temporal availability of water. The simulations include interacting representations of the spatially distributed system, the engineering system (including agriculture), the behavioral system (a market model), and the institutional system. Statistical experiments are run, using real people representing the various demand sectors, to explore the impacts of various types of potential water leasing institutions on the efficiency of reallocation of available water resources in the middle basin of the Rio Grande River in New Mexico. During implementation, stakeholders and water managers were able to comprehend and use the modeling system satisfactorily. The conceptual framework behind the water-leasing model is shown in Figure 2.

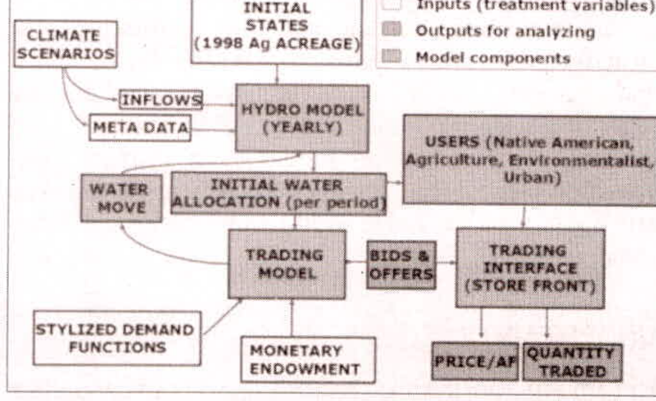

Fig. 2: Water-leasing Conceptual Model Framework

APPLICATION EXAMPLE: REGIONAL SCENARIOS

Scenario planning has not been fully utilized in environmental resource management studies due to a lack of formal guidance material on adopting a scenario development process. To that end a formal scenario development framework (see Figure 3) has been put forward as a means of promoting more scenario applications in the management field. The scenario development process is a five phase approach consisting of: scenario definition, scenario construction, scenario assessment, and risk management (Liu *et al.*, 2007c; Wagener *et al.*, 2006).

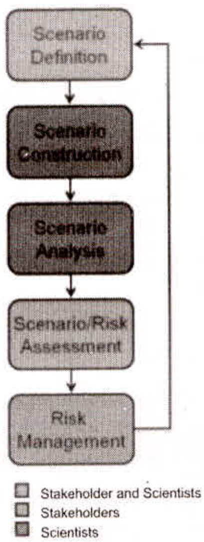

Fig. 3: Formal Scenario Development Process

The scenario construction phase identifies qualitative scenarios that are relevant to both scientist and stakeholder concerns. The scenario construction phase produces qualitative scenarios that are primed for model simulations. The Scenario analysis phase is devoted to conducting analytical techniques on the simulated output of the scenario modeling activity. The scenario assessment phase draws out the implications of the results found in the scenario analysis phase to management issues. Finally, the risk management phase uses the implications of the scenario simulations to drive certain response and management strategies. Risk management directly links scenario results to planning and decision-making strategies.

Each phase of scenario development involves scientists and stakeholders; with each taking a role in leading a phase as appropriate. Therefore the approach provides a synthesis of stakeholder-defined scenarios and science-based scenarios. As a result stakeholder needs and perspectives are also incorporated; adding political credibility and acceptance. The framework also proposes a uniform language and context to encourage uncomplicated collaborations with other scenario developers.

Regional scenarios in development for the US Southwest have been in development by a team of scenario developers covering a range of backgrounds; socio-economics, integrated modeling, stakeholder engagement, integrated assessment, climate impacts, and hydrology. Scenarios of interest to stakeholders and water managers in the southwest have directly targeted themes of land use change, population growth, and climate variability. These regional scenarios will be used to drive various regional sustainability models that target issues of vegetation change, riparian preservation, and water markets in the southwest.

CONCLUSIONS

The impending advent of water crises associated with dwindling resources and greater demand has pressured management practices to improve accordingly. In response to this situation, science can provide the information necessary to improve existing management strategies. However, much of current science is incompatible with active decision-making due to a large disconnect in objectives and priorities. Certain tools and methods can help assist water management in dealing with their contemporary issues as well as bridge the gap between the two schools of thought. One such tool is the use of numerical models to simulate system behavior for analysis. Along with numerical models, the notion of a conceptual model also serves to develop computational models by mentally building on the assumptions and relationships that constitute a simulation model. A conceptual model also serves as a communication tool between scientists and managers. In collaborating with decision-makers, scientists have an obligation to clearly share and discuss issues of uncertainty regarding the simulations to be performed; this builds trust and credibility amongst managers. Complimenting models are scenarios; descriptions of possible future states. Scenarios extend the usefulness of modeling into the future by exploring the effects of various system and policy changes to the benefit of decision-makers. A couple of applications utilizing these tools have been put to place in the American Southwest. Firstly, simulation models have been used to look into the plausibility of water-leasing markets as a tool to reallocate regional water supplies according to demand patterns. Secondly, regional scenarios have been developed in response to stakeholder concerns using a formal scenario development framework that is new to the environmental field. These applications serve as an example of the tools and strategies discussed in this paper, to encourage water managers looking for science inputs to help them achieve their goals.

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