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Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management

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Abstract

The call for more effective integration of science and decision making is ubiquitous in environmental management. While scientists often complain that their input is ignored by decision makers, the latter have also expressed dissatisfaction that critical information for their decision making is often not readily available or accessible to them, or not presented in a usable form. It has been suggested that scientists need to produce more "usable" information with enhanced credibility, legitimacy, and saliency to ensure the adoption of research results. In basin-scale management of coupled human-water systems, water resources managers, like other decision makers, are frequently confronted with the need to make major decisions in the face of high system complexity and uncertainty. The integration of useful and relevant scientific information is necessary and critical to enable informed decision-making. This paper describes the main aspects of what has been learned in the process of supporting sustainable water resources planning and management in the semi-arid southwestern United States by means of integrated modeling. Our experience indicates that particular attention must be paid to the proper definition of focus questions, explicit conceptual modeling, a suitable modeling strategy, and a formal scenario analysis approach in order to facilitate the development of "usable" scientific information. We believe that these lessons and insights can be useful to other scientific efforts in the broader area of linking environmental science with decision making.

Keywords: Integrated modeling; Decision support; Scenario analysis; Water resources management; Sustainability

1. Introduction

Science is increasingly being called upon to provide information for complex environmental decision making (e.g., Browning-Aiken et al., 2004, 2006; NRC, 1999; Matthies et al., 2007). However, despite recent remarkable advances in environmental science with growing availability of relevant knowledge, data, and information, how science can best support environmental decision making remains an outstanding question (Cash et al., 2003; Lee, 1993; Reichert et al., 2007; van der Sluijs, 2007). For example, the results of scientific research may not always be made available in the form required by decision makers (e.g., Jacobs, 2002); and lack of uncertainty estimates may render the results from scientific research not directly applicable to decision-making (e.g., Refsgaard et al., 2007; Xu et al., 2007). Since science and policy serve different purposes (Lee, 1993), scientists and decision makers typically maintain different values, interests, concerns, and perspectives and, more importantly, tend to lack a mutual understanding of each other's knowledge systems (Jacobs, 2002; McNie, 2007; Sarewitz and Pielke, 2007). This has led to huge knowledge gaps between science and decision making, and has hampered the effective flow of information across the boundary between knowledge and practice (Acreman, 2005;

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Cash et al., 2003; NRC, 1999). While scientists often complain that their voices have been ignored by policy makers, the latter have also expressed dissatisfaction that critical information required for decision making is often not readily available or accessible, or not presented in a usable form (e.g., Jacobs, 2002). Apparently, there is a need to improve the interface and communication between science and policy in order to enable improved environmental decision-making (e.g., Parker et al., 2002).

Recently, a great deal of discussion has been devoted to how to best bridge the gaps between environmental science and decision making, so that science produces useful or usable information in the context of decision making. Jacobs (2002) points out that for scientific information to be useful in a decision making process, it has to be (1) relevant to answering the specific policy question(s), (2) readily accessible and understandable by decision makers, (3) acceptable in terms of accuracy and trustworthiness, (4) compatible and usable in the specific decision making context, and (5) provided in a timely fashion (see also Jacobs et al., 2005). Along the same lines, other authors suggest that usable information is characterized by three essential attributes: *credibility* (information being dependable and of high quality as perceived by its users), *legitimacy* (information being transparent to and understandable by its users), and *saliency* (information being relevant to the specific context in which the decision is made) (e.g., Cash, 2002; Cash et al., 2003; Dilling, 2007; Logar and Conant, 2007; McNie, 2007; Sarewitz and Pielke, 2007). These characteristics of usable information call for new strategies to improve the science-policy interface and to develop effective bi-directional information flows between scientists and decision makers. Cash et al. (2003) promote the use of ‘‘boundary management’’ functions including communication, translation, and mediation and ‘‘boundary objects’’ such as models and scenarios to enhance the credibility, legitimacy, and saliency of information. Sarewitz and Pielke (2007) proposed a conceptual framework for reconciling the supply of and demand for science as a way of connecting science and decision making. Lemos and Morehouse (2005) suggest a strategy of co-producing science and policy in an iterative process of regular interaction between scientists, policy makers, stakeholders, and the public. Parson (1995) suggests that models can be used as an effective means to link the results of scientific research to policy making, particularly in the area of *integrated assessment*. Xu et al. (2007) proposed an ‘‘appropriateness’’ framework that can help to develop decision support models with appropriate levels of complexity to stimulate effective communication between decision makers and modelers. Ticehurst et al. (2007) discussed an integrated modeling framework based on Bayesian Networks that allows active participation of relevant stakeholders and explicit consideration of uncertainty (see also Castelletti and Soncini-Sessa, 2007a). Along the same lines, other authors have promoted ‘‘participatory modeling’’ as a strategy to improve participation where decision makers, like the modelers, are involved in all phases of the model identification process (e.g., Castelletti and Soncini-Sessa, 2006, 2007b; Gaddis et al., 2007). In summary, the call for improved communication between scientist and decision makers is ubiquitous in all areas of environmental policy making including land use management and water resources management (e.g., Callahan et al., 1999; Schiller et al., 2001; Siepen and Westrup, 2002).

In basin-scale management of coupled human-water systems, water resources managers, like other decision makers, are frequently confronted with the need to make major decisions in the face of high system complexity and uncertainty. The integration of useful and relevant scientific information is necessary and critical to enable informed decision making. However, how to establish effective communication between science and policy to generate useful information in a specific decision context remains a major challenge (e.g., Callahan et al., 1999).

This paper aims to address some of the critical issues involved in bridging environmental science and decision making by describing some aspects of what has been learned from an ongoing 10-year integrated modeling effort aimed at improving support for water resources decision making in the semi-arid southwestern United States. The project involves a multi-institutional, multi-disciplinary research team supported by the National Science Foundation (NSF) Science and Technology Center for Sustainability of Semi-Arid Hydrology and Riparian Areas (SAHRA, www.sahra.arizona.edu). The modeling approach involves activities that facilitate the development of a good balance between credibility, legitimacy, and saliency of information produced through various communication, translation, and mediation strategies. The application of integrated modeling to a specific SAHRA context was not, however, straightforward and we encountered practical issues such as how to start and move forward with a complex integrated study which investigates multiple system components and dimensions, and involves researchers, experts, and stakeholders from a broad range of disciplines and institutions/agencies. Although research in support of environmental decision making is by nature context-dependent, we believe that the lessons and insights learned from the SAHRA integrated modeling effort can inform other similar scientific efforts elsewhere around the globe in the broader area of linking environmental science with decision making. While the full integration of science and decision making also entails favorable changes in science policy and institutional infrastructures (e.g., Browning-Aiken et al., 2004, 2006), this paper will focus on what scientists and researchers can do to generate knowledge in a form more ‘‘usable’’ to and supportive of decision making.

Section 2 will elaborate on the concept of integrated modeling and why it is perceived as an advantageous strategy for producing ‘‘useful’’ knowledge for contemporary water resources decision making (i.e., Integrated Water Resources Management or IWRM). In Section 3 we review the SAHRA Integrated Modeling approach as a case study. Section 4 details the issues encountered in and experiences learned from this effort and how these experiences have enabled the overall effort of supporting decision making to achieve greater success. A generalized framework for pursuing integrated environmental modeling in the context of decision support is proposed and detailed in Section 5. The paper concludes in Section 6 with comments on the broader impacts of these insights and some recommendations for future research.

2. Integrated modeling for sustainable water resources management

Throughout history, water resources have often been managed in a fragmented manner so that decisions made to meet the demands of a user typically failed to consider the impacts of those decisions on other (competing) users and on the health of the entire ecosystem (NRC, 1999). As water resources around the globe come under increasing pressure due to continuous population growth and economic development, it is critical to adopt a management policy that can lead to *sustainable* water supply and use, i.e., a policy that meets ‘‘the needs of the present without compromising the ability of future generations to meet their own needs’’ (Gleick, 1998). As a new strategy for sustainable development, the concept of Integrated Water Resources Management (or IWRM) emerged from the first Dublin principle for freshwater management identified during the 1992 International Conference on Water and the Environment in Dublin (Mitchell, 2005). The first Dublin principle recommended that water problems be considered in relation to land-use planning, socioeconomic development, and the protection of other natural resources. This is well-captured by the definition of IWRM by the Global Water Partnership (GWP, 2000):

> A process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Since its emergence in 1992, a great deal of research has been devoted to IWRM in both developed and developing countries throughout the world (e.g., Ashton et al., 2006; Barreira, 2006; Cardwell et al., 2006; Davis and Threfall, 2006; Lanini et al., 2004; Mitchell, 2005, 2006; Mostert, 2006). IWRM shares its emphasis for holistic investigations with other similar strategies such as the watershed approach (e.g., NRC, 1999), the ecosystems approach (e.g., Grumbine, 1994, 1997), the coupled human-environment systems approach (e.g., Turner et al., 2003; Monticino et al., 2007; Yuan et al., 2007), integrated assessment (e.g., Jakeman and Letcher, 2003; Parson, 1995; Matthies et al., 2007), and multi-criteria decision analysis (e.g., Hill et al., 2005). In these approaches, decision making is to be based on sound scientific knowledge and understanding by considering the natural system and the human environment (including the complex interactions between the two) in an integrated fashion. It is critical to appreciate that this *integrated* perspective is different from the *comprehensive* approach which seeks to examine all variables and relationships within an entire river basin defined in the broadest possible way, as used in comprehensive river basin planning and management (e.g., Mitchell, 1983). Instead of trying to be comprehensive, which is often neither necessary nor feasible, an ‘‘integrated’’ approach maintains the benefits of a systems perspective by ‘‘focusing on the key components and relationships accounting for the greatest variability in system behavior’’ (Mitchell, 2005 and 2006).

IWRM and other holistic management concepts are very difficult, if not impossible, to achieve through pure data collection or process studies. Recently, integrated modeling—the modeling of interactions within and between natural and human systems—has emerged as a strategy to tackle the complexity and uncertainty faced by contemporary water resources and land use management (e.g., Bloyd et al., 1996; Browning-Aiken et al., 2006; Cai et al., 2003; Jakeman and Letcher, 2003; Lanini et al., 2004; Letcher et al., 2004; Oxley et al., 2004; Wilby et al., 2006; Nguyen et al., 2007). On one hand, by investigating the relationship between the natural water system and the human environment under a single framework, the integrated approach allows decision makers to consider natural, social, and economic factors and to deal with the complexity and interconnections within and between natural and human environments. On the other hand, modeling can help to integrate knowledge and data by embedding the best science available and by moving science into widespread usage for water resources management. It clearly also offers flexibility and the possibility for sensitivity and uncertainty analyses, thereby ensuring a certain degree of internal consistency, robustness, and transferability (e.g., Nguyen and de Kok, 2007). Together, the integrated modeling approach offers a systematic mechanism to produce and assemble information from multiple domains and disciplines in a format that is most useful and acceptable to decision makers (Parson, 1995).

At its most fundamental level, IWRM is a process of reconciling the demand for water by the human environment with the supply of water by the natural system to achieve sustainability (GWP, 2000). Accordingly, integration for the purpose of IWRM needs to occur both within and between the natural system and the human environment. This, dependent on the specific decision problem, may require the integration of land and water management, of surface water, groundwater, and evapotranspiration, of water quality and quantity, of upstream and downstream water uses, of water and wastewater management, and of all stakeholders in the planning and management processes (GWP, 2000). To enable key integration via modeling, a multi-disciplinary strategy is necessary so that the biophysical, chemical, engineering, socio-economic, and institutional dimensions of the couple human-environmental system can be considered within a single, coordinated framework (Wagener et al., 2005). As an illustration of the IWRM concept, the SAHRA integrated modeling case study is described in relevant detail in the next section.

3. Overview of multi-resolution integrated modeling in SAHRA

SAHRA is a Science and Technology Center (STC) founded by the US National Science Foundation to investigate and help improve the sustainable use of water resources in arid and semi-arid regions (Sorooshian et al., 2002), by exploring how cutting-edge science can be pursued in support of water management and decision making. SAHRA frames its science and stakeholder activities in a river basin context, with primary geographical focus on four semi-arid river basins in the southwestern United States and northern Mexico: the Upper San Pedro, the upper Rio Grande, the Salt-Verde, and the Rio Conchos (Fig. 1). In these river basins, limited sources of water interact with a rapidly growing population and have resulted in increasing water stress with strong competition among multiple beneficial uses. This situation has led to considerable overdraft of groundwater, which has resulted in subsidence problems, and the disappearance of much of the riparian habitat (Springer et al., 1999). Three water-related issues have been deemed to be of particular importance to support sustainable water resource management in these areas:

(1) An extensive ongoing transition of the landscape from historical grassland to shrub land dominated by woody species;
(2) A continued loss of natural riparian habitat aggravated by the invasion by non-native species such as tamarisk (saltcedar);
(3) The need for mechanisms for effective and efficient allocation of water among competitive uses, while maintaining appropriate checks and balances to prevent lasting and irreversible environmental damage.

To address these issues, SAHRA has focused its scientific research and modeling activities on three stakeholder-relevant integrating science questions (or focus questions), which are critical for the wise management of water resources in semiarid regions and can only be addressed by collaborative research operating in center mode through the consistent deployment of integrated, multidisciplinary science. These three questions are:

(1) What are the impacts of vegetation change on basin-scale water balance?
(2) What are the costs and benefits of riparian preservation and/or restoration?
(3) Under what conditions are water markets and water banking feasible?

In developing a modeling strategy to address such questions, SAHRA has adopted a ‘‘multi-resolution’’ approach to integrated model development, with each resolution targeted towards different questions (http://www.sahra.arizona.edu/research/IM/index.html). Different models constructed at three overlapping resolutions are loosely integrated in a single framework so that the feedback among multiple interacting components is inherent in the simulations (Fig. 2). The three model resolutions are: (1) coarse (units being river reaches and sub-basins), (2) medium (units being 1–12 km grid cells), and (3) fine (units being grid cells of 100 m or smaller). The *fine resolution modeling* (FRM) approach provides a scientific computational foundation for water resource decision-making by coupling detailed physical models of vegetation, land surface hydrology, and groundwater hydrology (Winter et al., 2004). It is designed to answer the first integrating question by examining the effects of vegetation change on the water balance of the upper Rio Grande Basin. In contrast, the goal of the *coarse resolution modeling* (CRM) approach is to implement the best possible high-level representation of the ‘‘behavioral’’ (primarily socio-economic) and ‘‘institutional’’ aspects of the human environment, coupled with a moderately simplified representation of the underlying ‘‘physical’’ eco-hydrological system and the ‘‘engineering’’ components that link the natural and anthropogenic worlds. Finally, the goal of the *medium resolution modeling* (MRM) approach is to bridge the (potentially sizeable) gap between the rigor and detail about natural system physics (hydrological and ecological aspects) embedded in the FRM and the rigor and detail about human system behavior (institutional and socio-economic aspects) embedded in the CRM; at this level, particular attention is given to proper representation of resource allocation, engineering and land use management aspects of the system, constituting a interface between the natural and socio-economic-institutional layers. Different components from the MRM and CRM are linked together to address the second and third integrating questions, regarding the costs/benefit of riparian restoration and the feasibility of water markets/banking, respectively. This multi-resolution, multi-disciplinary approach can effectively facilitate the flow of physical understanding from detailed natural system models to coarse-scale engineering and policy models, and the flow of behavior understanding and policy constraints/regulations in the opposite direction.

All these different modeling activities are guided and integrated through developing and assessing a series of regional and local scenarios that represent a broad range of

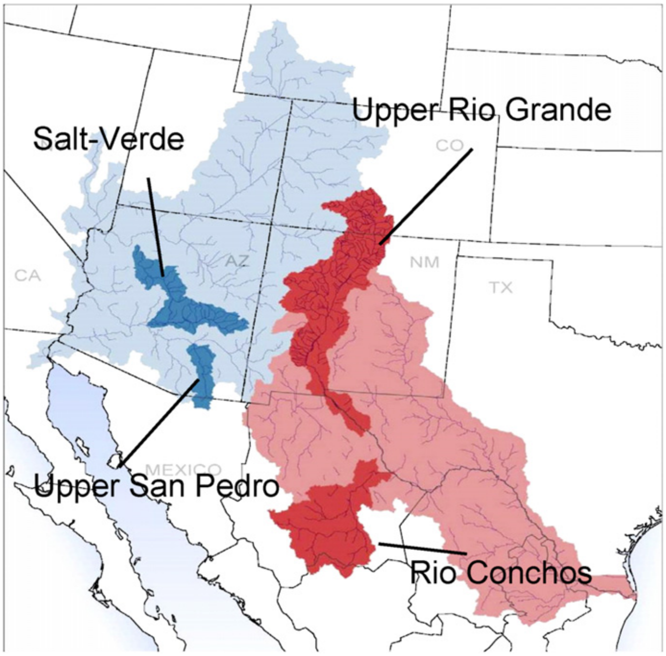

Fig. 1. The focus basins of SAHRA Integrated Modeling effort.

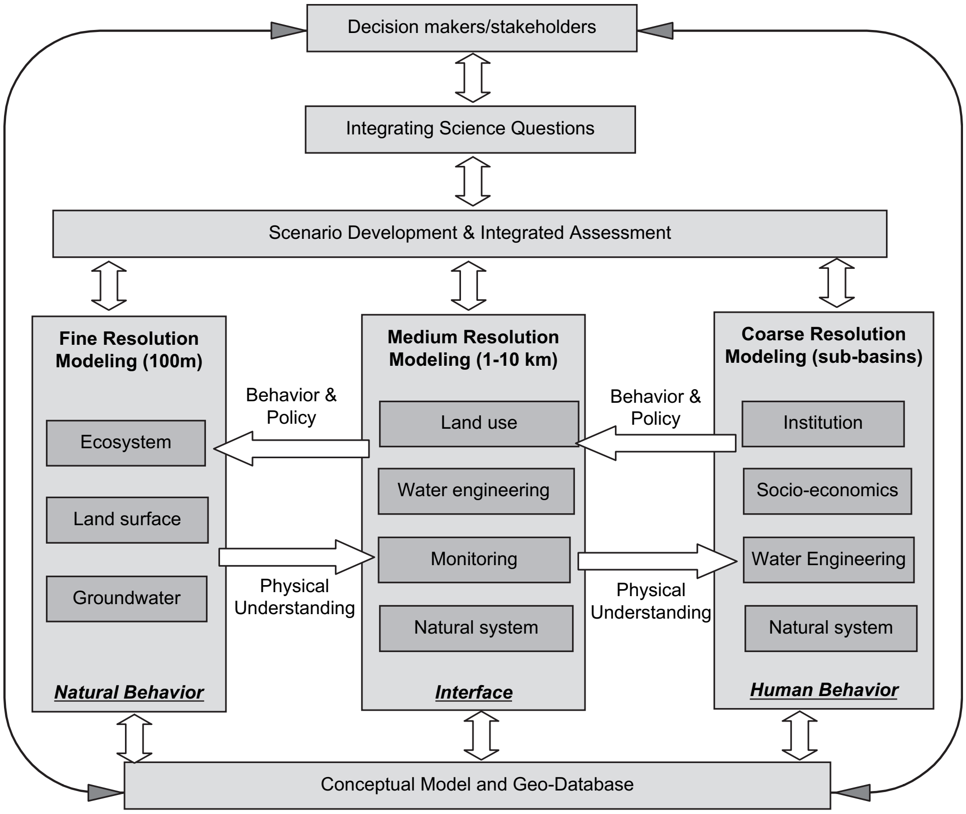

Fig. 2. SAHRA's multi-resolution, multi-disciplinary framework for integrated modeling of coupled human-environmental systems.

future natural and socioeconomic conditions in the southwest United States. As a way to build synergies between the different activities, the scenario development within SAHRA is based on the three integrating questions and takes into account the interactions of different components as shown in Fig. 2. On the other hand, these modeling activities are supported by the development of a common underlying conceptual model and a geospatial database that is closely coupled with other data collection and process studies. The multi-disciplinary, multi-resolution integrated modeling and evaluation framework outlined in Fig. 2 can be used to assess impacts of climate variability and land use change on water resources management in semi-arid river basins around the world. Interested readers are referred to Wagener et al. (2005) for a more detailed description of the SAHRA integrated modeling strategy.

4. Lessons learned from SAHRA integrated modeling

The above multi-resolution integrated modeling framework serves as an effective and efficient vehicle to achieve SAHRA's major scientific tasks in support of water resources management as described in Section 3. However, the implementation of such an integrated framework within the specific SAHRA context was not straightforward in the beginning. We encountered practical issues such as how to focus the various kinds of research efforts of scientists and to integrate them with the interests of relevant stakeholders, how to determine the appropriate levels of complexity of the integrated models for addressing different science and policy aspects, and how to effectively engage and communicate with decision makers. In trying to resolve these issues, we learned many useful lessons from the SAHRA integrated modeling case study (hereinafter referred to as SAHRA IM) on the effort that must be made to better integrate science into decision making so as to improve water resources management at the basin scale. Several important points are described below in detail, with a particular focus on how they can contribute to improving the credibility, legitimacy, and saliency of scientific information.

4.1. Importance of identifying focus questions

In any given river basin or watershed, numerous sets of human and environmental factors operate simultaneously, and it is neither feasible nor desirable to model all variables and interrelationships within a complex human-environment system. Hence, it is critical to first identify a limited set of focused science questions that can adequately address the major concerns of the decision makers and relevant stakeholders in the basin (Letcher et al., 2004; NRC, 1999). In fact, question definition, or problem formulation, is considered as a crucial first step of any modeling project in many fields, followed by other typical modeling tasks including conceptualization, model development, verification and validation, model simulation, and implementation of results (e.g., Brooks, 2006; Wang and Brooks, 2006). Projects involving large-scale integrated water resources management are typically collaborative, multi-disciplinary, labor intensive, and time consuming, so that starting with well-defined focus questions is particularly important; it would be prohibitively expensive to start over if it is discovered at a later stage of the project that efforts are guided by a set of inappropriate science questions. Nevertheless, this seemingly important step can often be given insufficient attention by researchers who tend to go directly to model selection/building with only a very general and vague objective in mind.

Careful statement of the science questions to be addressed is essential to defining the overall modeling context, which in turn determines the modeling objectives and sets the boundaries for the modeling system(s). Only after the focus questions have been clearly identified, can proper research infrastructure be established to develop appropriate modeling systems and gather appropriate data for analyzing the problem and alternative solutions. Well defined focus questions can also help to determine which processes should be modeled and which should be left out of the integrated modeling system. For collaborative projects that involve researchers and stakeholders from different disciplines and institutions, these focus questions can also serve to integrate and encourage people from different backgrounds to think and work in a coordinated manner toward addressing the same relational and behavioral issues.

The definition of focused research questions is a nontrivial task, requiring not only an adequate scientific investigation, but also the integration of input from all interested and relevant parties, including scientists, decision makers, stakeholders, and even the public-at-large (Letcher et al., 2004; NRC, 1999). This, therefore, provides the benefit for engaging and attracting relevant parties at the earliest possible stage and potentially maintaining these interactions throughout the life cycle of the project. Letcher et al. (2004) pointed out that, for integrated assessments, the focus questions should be both specific enough (so that they are tractable to the integrated modeling approach) and general enough (so that the results remain relevant after the research is completed). This applies to integrated water resources management as well. By taking into account the concerns of decision makers and stakeholders in the formulation of focus questions, we can ensure that the information resulting from the research effort is of interest to decision makers, thus enhancing the saliency (and indirectly, the credibility and legitimacy) of the information to be produced.

In our experience, the research problem was too broadly defined at the beginning of SAHRA IM effort, in terms of assessing the potential impacts of climate change on water resources management in the southwest United States. This led to the initiation of a wide range of different modeling projects and process studies which were initially grouped into the following five "Thrust Areas" based on the capabilities and interests of researchers involved: (1) spatial and temporal components of the water balance, (2) basin-scale water and solute balances, (3) functioning of riparian systems, (4) multi-resolution integrated modeling of basin-scale processes, and (5) water as a resource: competition, conflict, planning, and policy. To develop an integration of research efforts across the center, the projects were later reorganized into "Themes Areas" and then further into three "Macro-Themes" including (1) basin-scale water balance, (2) river systems, and (3) integrated modeling. This helped to better focus and manage the projects and to improve the level of integration between activities in SAHRA. However, it was noticed that, although each of the early-stage studies generated very useful results from a scientific point of view, some of these projects were of limited value in meaningfully addressing the major concerns of the decision makers and stakeholders in the study basins. From the point of view of pure decision support, investment in these earlier projects constituted an inefficient use of time and other resources.

Accordingly, a comprehensive review and evaluation of all modeling and other research efforts was performed during the third year; and three integrating science questions were defined (in consultation with relevant decision makers and stakeholders) and used to reorganize and prioritize all the activities. The three integrating questions (see Section 3) are broad enough to enable engendering and crosscutting key research topics of relevance, and are also specific enough to touch on scenarios that are of prime interest in the study basins such as land use changes, population growth, and climate variability. Once the focus questions were clearly defined, the SAHRA IM activities became better structured and planned. This reorganization of modeling activities (and associated process research) around the three focus questions has ensured that each project is directed towards making a clear and necessary contribution to answering one or more of the three focus questions. As such, a synergy of activities has been achieved which is helping to drive science integration and, because stakeholder issues are tied to the research efforts, also to ensure the ultimate application of research results in decision making. Overall, the evolution of SAHRA research from "Thrust Area", interest-based efforts to those supportive of answering the stakeholder-driven science questions reflects the advantage of using focus questions as a mechanism for establishing an effective research infrastructure in a specific decision context.

4.2. Importance of explicit conceptual modeling

If problem formulation is the important first step of a modeling project, the development of a suitable conceptual model should be the crucial step that follows. This is particularly important for a multi-disciplinary integrated model effort in support of decision making. As the name suggests, conceptual modeling, or conceptualization, is the process of abstracting a model from a real or proposed system, with an appropriate level of simplification of reality (Robinson, 2006). Along this line, a conceptual model (sometimes also referred to as a modeling framework in the literature) can be defined as a "*non-software specific description of the simulation model that is to be developed, describing the objectives, inputs, outputs, content, assumptions and simplifications of the model*" (Robinson, 2004). As such, conceptual models are designed to capture, at an intuitive level, the essential system components, relationships and their dynamics, and can therefore be used as effective "communicative" vehicles for building common understanding of the complex modeling system among researchers and stakeholders (van der Zee and van der Vorst, 2005). From a modeling perspective, an explicit, formalized conceptual model bridges the gap between focus questions and the real simulation model by an articulation of what is to be modeled, how it is to be modeled, and what data are required. Being a repetitive and adaptive process, conceptual modeling also makes it easier to incorporate stakeholder input at any point of the project and feedback from subsequent model validation and verification.

Nevertheless, as with problem formulation, conceptual modeling has received insufficient attention. Numerical modelers traditionally tend to develop their modeling systems in an implicit way, guided by their own mental reference models. Models built in such a way typically have limited transparency and completeness, the two most important attributes for establishing credibility among stakeholders (van der Zee and van der Vorst, 2005). While the call to improve communication is ubiquitous in decision support, scientists may often not realize that lack of transparency and completeness (i.e., lack of explicit conceptual models) can constitute one of the major factors responsible for failures in communication (McNie, 2007).

In the course of SAHRA IM development, we learned similarly that the credibility, legitimacy, and saliency of information can be enhanced by establishing an explicit conceptual model to form a common conceptual basis (across modeling resolutions) for improving mutual understanding and communication among researchers (from different disciplines) and stakeholders. At the beginning of the SAHRA IM effort, the importance of an explicit common conceptual model was not recognized, rendering it very difficult to communicate even within ourselves, not to mention to communicate with the stakeholders. Hence, to support the multi-disciplinary integrated modeling activities and the communication with stakeholders, a critical SAHRA task was launched in the fourth year, involving the ongoing development and refinement of a common conceptual framework (1) to ensure that the different models concerning the three integrating science questions represent the real situation adequately in physical, engineering, socio-economic, and institution dimensions; (2) to ensure that the different models at fine, medium, and coarse resolutions are consistent with each other; and (3) to facilitate communication among modelers and stakeholders/decision-makers. This overall conceptual framework provides an enhanced vehicle for communication among modelers and stakeholders/decision-makers. It helps to identify the appropriate level of model complexity that is both understandable and credible among the stakeholders. Additionally, the conceptual models provide an anchor for monitoring/traceability that enables the stakeholders to recognize errors and limitations of the integrated models, impacts of changing assumptions, etc., allowing the analysis and modification of modeling scenarios to be conducted in a more efficient and responsive manner. For example, the conceptual model helps the stakeholders to recognize, and thus appreciate, that certain external factors of concern, such as energy prices and technology advances, are not explicitly parameterized in the modeling system and can only be indirectly (and somewhat arbitrarily) related to the model inputs, which may introduce additional uncertainty into the scenario outcomes (see Section 4.4).

4.3. A multi-resolution, multi-disciplinary integrated modeling approach

Given the multi-disciplinary, complex nature of an IWRM problem, it seems neither achievable nor desirable to aim for a single computational ‘‘super-model’’ that attempts to represent a consolidated view of all available knowledge acquired about the system at a single resolution. In fact, different water resources issues may occur at different temporal and spatial scales and thus may lend themselves to different types and resolutions of modeling effort (e.g., Letcher et al., 2004). For example, a question related to estimates of basin-outlet stream flow might most efficiently be addressed by a coarse resolution lumped modeling approach, whereas questions concerning the complex interactions between vegetation and water or related to the sources and natures of pollutant may require a fine-scale distributed modeling approach. For an integrated modeling approach, the typical concurrence of natural and human processes of different scales necessitates striking a balance between model simplicity and complexity through, for example, using nested and linked models of varying degrees of complexity applied to the same region or problem.

From a decision support point of view, the level of complexity to be built into an integrated modeling framework is most appropriate when it can effectively link modeling and modeling results to decision making. Ideally, the integrated models should be both detailed/complex enough, so that they are credible among both scientific and decision making communities and simple enough that they can be easily understandable by the decision makers. In practice, it is common to observe greater emphasis on the number and range of components built into decision-support modeling systems than the level of detail on individual components (note the reverse is typically true for traditional research-oriented modeling systems). As a result, decision support systems tend to show more breadth than depth, with more focus given to linking together simple modeling components rather than on preserving scientific rigor. This allows the modeling framework to run quickly and interactively on a computer by a decision maker; it, however, may degrade the credibility of the modeling results due to insufficient scientific rigor. The decision makers must feel a sense of confidence that the modeled representation is sufficiently realistic before being willing to accept the validity of the computational results, which is particularly true when the model provides results that seem counter-intuitive. This highlights a critical issue associated with the appropriate level of model complexity of decision support tools—the trade-off between credibility, legitimacy, and saliency.

A multi-resolution modeling approach was adopted and maintained from the very beginning of SAHRA IM development and has served as an efficient and effective way to integrate a range of disciplines, scales, complexities, decision makers, and stakeholders (Fig. 2). The three distinctive resolutions were chosen to match the scales of different processes to achieve both scientific and social robustness and decision support flexibility. For example, a grid size of 100 m at the finest scale was selected so that eco-hydrological understanding and data acquired at the plot-scale (experimental scale) can be properly assimilated into the model; the coarse (sub-watershed) scale modeling effectively addresses institutional and socioeconomic issues and is designed for interfacing with the decision makers; and the medium resolution modeling focuses on engineering and land use/land management issues and serves as a bridge between the other two resolutions. This enables the flow of knowledge about the physical system from the fine resolution system to the medium resolution system, to the coarse resolution system through to decision makers and the flow of understanding of human dynamics and decision perspectives in the other direction. A central focus of this framework is to provide a vehicle by which scientific understanding can be effectively and efficiently shared with the decision makers and stakeholders to enable informed decision making.

4.4. The formal scenario analysis approach

Uncertainty constitutes another important barrier to linking science with decision making. Despite the increasing availability of environmental observations and enhanced capability of environmental models, predicting the future is unavoidably fraught with uncertainties (Wagener and Gupta, 2005). *Scenario analysis* is a practical, effective way to put integrated environmental models into more beneficial use for long-term real-world decision making under uncertainty. Decision makers frequently use the scenario approach in their daily decision making processes, suggesting that scenario analysis can be an effective way to integrate environmental modeling with decision making. In fact, if the identification of focus questions is an important first step towards linking science with decision making, it is with scenario analysis that the details of the decision perspectives are fleshed out to enable the final adoption of research results and to achieve a true integration.

The Intergovernmental Panel on Climate Change (IPCC) defines a scenario as ‘‘a coherent, internally consistent and plausible description of a possible future state of the world’’ (Houghton et al., 1995). Scenarios are not forecasts or predictions; nor do they project the ‘‘most likely’’ future. Instead, a scenario analysis study tackles the uncertainty involved in decision making by investigating a representative spectrum of plausible alternatives for the future to (1) understand impacts stemming from alternative conditions; (2) to assess potential risks and opportunities; and (3) to identify ways to respond to risks and opportunities, thus enabling improved decision making and assessment. In a scenario approach, key decision variables, both highly important and highly uncertain, determine the themes to be addressed by the scenarios; quantitative and qualitative information are then determined and used to derive input data needed by an integrated environmental model to construct the scenarios. Through analysis of scenario outcomes, the uncertainty associated with decision making and their impacts are better understood, so that decision makers have greater confidence in the costs and benefits associated with a certain decision. As the future unfolds, scenarios are reviewed and evaluated to determine which scenarios are converging or diverging from the actual evolving future, and whether the current scenarios should be modified or if new scenarios are needed. As such, scenario analysis is perfectly situated for the emerging idea of ‘‘adaptive management’’ for improved decision making (e.g., Hollings, 1978; Lee, 1993; Murray and Marmorek, 2003). Liu et al. (in press) proposes a formal approach to environmental scenario planning, where scenario development is described as an iterative process of five progressive phases: scenario definition, scenario construction, scenario analysis, scenario assessment, and risk management.

For IWRM studies, the process of scenario development typically involves making explicit and/or implicit assumptions about potential future conditions, such as climate change, land cover and land use changes, population growth, economic development, and technological changes. Realistic assessment of scenario impacts often requires complex integrated modeling frameworks that represent both the physical and socioeconomic systems to the best of our knowledge. Enhanced environmental modeling from integrating multiple disciplines and stakeholders leads to better understanding and more rigorous evaluation of scenario impacts, which, in turn, results in improved decision making. Hence, scenario analysis can also serve as an integrator of different modeling and process studies towards more effectively linking science with decision making.

Ideally, a scenario effort should start as early as the focus questions are defined. Nevertheless, as with problem formulation and conceptual modeling, the development of scenarios did not receive sufficient attention during the early years of the SAHRA IM effort. Instead, modeling activities were guided by a single scenario to evaluate the impact of a 1950s drought combined with the current land condition and population growth on the basin-scale water balance. However, it was later found out that this single scenario could not adequately represent the spectrum of plausible alternative futures the decision makers would like to consider. For example, it is believed that the 1950s drought is not severe enough for scenario planning as we may experience worse drought conditions during the 2000s. To achieve effective decision support, a formal scenario planning approach (e.g., Liu et al., in press) should be adopted to develop a set of well conceived and parameterized scenarios, an effort involving both scientists and stakeholders.

In response, a scenario research team consisting of seven scientists from a wide range of backgrounds has been established within SAHRA to develop a set of regional and local scenarios (in collaboration with relevant stakeholders and decision makers) as a way of effectively applying SAHRA integrated models to decision problems as outlined by the three integrating science questions. We adopt the formal approach outlined in Liu et al. (in press) to develop the scenarios through an iterative process including five progressing phases: *scenario definition*, *scenario construction*, *scenario analysis*, *scenario assessment*, and *risk management*. Driven by stakeholder concerns, potential future alternatives (or scenarios) are being defined, constructed, analyzed, and assessed to characterize key uncertainties and to inform decision makers and stakeholders about how to address risks in decision making processes. In this overarching effort, integration of local, regional, and global scenarios for different SAHRA projects across the three science questions is essential. SAHRA will ultimately be judged on the quality of the answers to the scientific and policy questions it addresses and the degree to which SAHRA research is applicable to questions that will arise in the future. By actively promoting the dialogue between researchers and stakeholders, the new scenario effort is playing a critical role in broadening the applicability of SAHRA IM research and in further strengthening the linkages among different SAHRA projects, and most importantly, those between SAHRA research and the needs of decision makers. As indicated in Fig. 2, the scenario development effort is the driving force of all model activities within SAHRA and would have influenced the development of the integrated models to a greater degree if it was launched from the very beginning (or in an earlier phase) of SAHRA.

5. A framework for linking modeling with environmental decision making

Drawing upon the lessons learned from the SAHRA IM effort on decision support (as discussed above in Section 4) and other environmental modeling frameworks discussed in the literature (e.g., Refsgaard and Henriksen, 2004; Jakeman et al., 2006; Refsgaard et al., 2007), we propose a generic framework for performing integrated modeling efforts in an effective and efficient manner to achieve the best possible decision support (Fig. 3). If given a chance to start over with the SAHRA IM effort, we would follow the steps outlined in this framework as follows:

(1) identify and formulate a limited set of integrating focus questions based on scientific investigations and stakeholder input;
(2) define a set of well-conceived scenarios based on the focus questions and further input from stakeholders and other experts on the key external forcings that are both highly important and highly uncertain;
(3) develop an underlying conceptual basis for the numerical models to be built to construct the scenarios defined in step 2;
(4) develop the numerical integrated modeling system; test the model with a rigorous code verification and model calibration/validation strategies and adjust the conceptual model until satisfaction with the model performance is achieved;
(5) construct each scenario by deriving proper model inputs, running the model, and collecting the desired scenario outputs;
(6) perform an indicator analysis on the scenario outputs; conduct a sensitivity analysis to understand main controls and sources of uncertainty; assess/compare the impacts of each alternative scenarios;

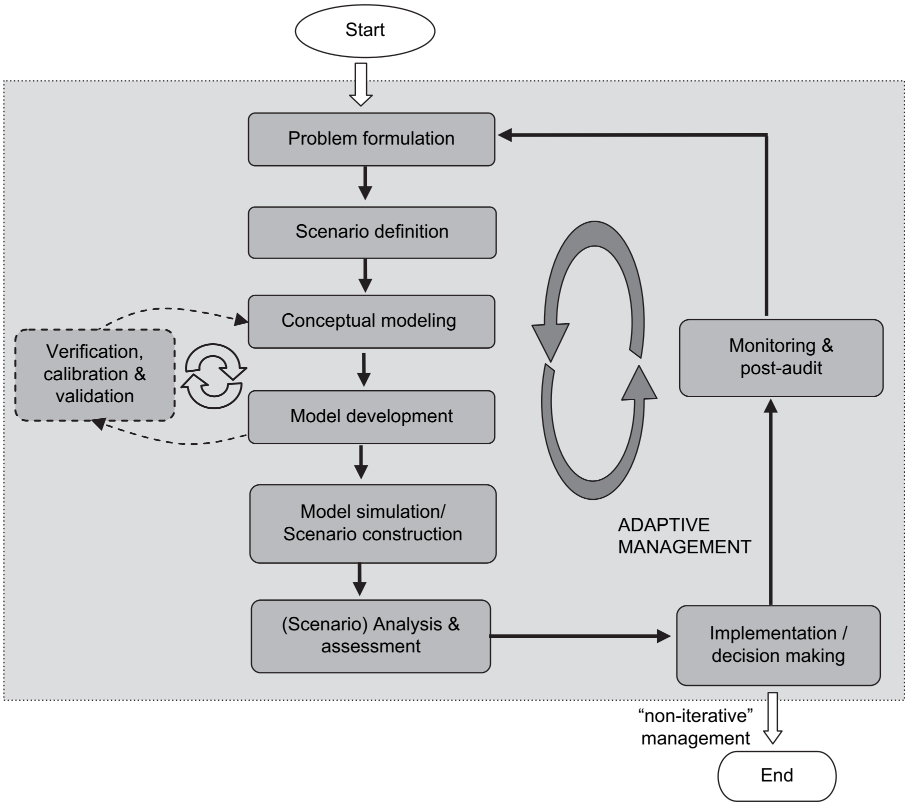

Fig. 3. A generic framework for effective decision support through integrated modeling and scenario analysis.

(7) deliver the scenario assessment results to decision makers (who will in turn make an implementation of the results);
(8) terminate the process if an ‘‘non-iterative’’ decision support effort is desired; or
(9) proceed with monitoring and post-audit of the implemented plans and, when necessary, adjust the focus questions to begin another iteration of modeling tasks for the purpose of ‘‘adaptive management’’, an emerging concept for contemporary environmental management and planning.

More detailed guidelines for implementing each of the above steps are provided in Table 1. Note that these guidelines are illustrated from a decision support point of view, with a focus on how to effectively incorporate the stakeholder perspective to produce more ‘‘usable’’ scientific information; it is, however, useful to be aware that ensuring scientific soundness in each of the steps can be equivalently challenging and critical (e.g., Refsgaard and Henriksen, 2004). For environmental modeling to be effectively and efficiently applied to decision making, it is essential that the researchers (and other participants) follow these steps so that the investment in time and other resources is most cost-effective and the important information is supplied in a timely fashion for decision making.

6. Summary and discussion

Integration of science with decision-making represents one of the most difficult challenges of environmental management. Arguably, enhancing the credibility, legitimacy, and saliency of information being produced can lead to more effective and proper usage of science products and thus better informed decision making. This calls for improved communication with and active engagement of decision makers, stakeholders, and all other parties that are interest in or relevant to the specific decision problem to ensure the adoption of research results.

Using the SAHRA integrated modeling effort as a case study, this paper illustrates several key points that deserve attention of researchers when modeling is adopted as a strategy for supporting complex environmental decision making. In

Table 1
Guidelines in implementing the modeling framework

Steps	Guidelines
Problem formulation	• Understand the decision context in both natural and human aspects • Identify key policy questions of interest to relevant stakeholders and develop interdisciplinary and integrating focus science question accordingly
Scenario definition	• Involve stakeholders extensively in this activity • Identify the key forcings to the system under study such as climate change or population growth • Determine the spatial extents and time horizons of the scenarios • Adopt appropriate scenario types in accordance with stakeholder concerns
Conceptual modeling	• Determine the system components/processes and the level of detail to be modeled • Specify appropriate temporal and spatial resolutions • Use alternative conceptual models to account for uncertainty about our knowledge of reality if desired • Be transparent about the assumptions and limitations of the conceptual model • Use a common language and explicitly document the conceptual model for communication with stakeholders
Model development	• Develop or select suitable computer models for scenario experiments • Be transparent about the capabilities and limitations of the model codes • Design and develop user friendly interfaces for stakeholder interaction
Verification, calibration, & validation	• Define performance criteria tailor-made to the specific decision context • Define the limits of performance accuracy acceptable to the stakeholders • Use independent data for code verification, model calibration, and model validation • Document the domain of applicability and degree of accuracy of the model
Model simulation/scenario construction	• Derive/gather model input datasets to run the scenarios • Collect model/scenario outputs that are of interest to the stakeholders
(scenario) Analysis & assessment	• Perform uncertainty assessment on the scenario outputs consider all the potential uncertainty sources introduced during every previous step • Discuss with stakeholders about appropriate indicators that are most valuable for decision making • Perform an indicators analysis to assess the potential risk associated with each scenario
Implementation/decision making	• Communicate the scenario results to the stakeholders along with uncertainty estimates • Maintain active/continuous support to and dialogue with stakeholders
Monitoring & post-audit	• Continuously monitoring (in collaboration with the stakeholders) key decision variables and evaluating the indicators as the future unfolds • Determine whether the current plans should be modified or if new scenarios are needed

particular, the importance of well-defined focus questions, explicit conceptual modeling, a multi-resolution strategy, and a formal scenario analysis approach is discussed in detail, with a focus on how these techniques can facilitate production of ''usable'' information with enhanced credibility, legitimacy, and saliency. Based on what has been learned from the SAHRA IM effort, a generic framework is proposed for performing an integrated modeling effort in an effective and efficient manner to achieve the best possible decision support. Regardless of the variability of the decision context from one project to another, the lessons learned from SAHRA integrated modeling can be useful to other scientists working in a decision support environment, particularly on how diverse sets of information, stakeholders, resources, and scientific ideas can be integrated into an effective decision support framework.

It is worth noting, however, that experience gained from SAHRA integrated modeling alone does not sufficiently address all the issues involved in bridging science and decision making. For example, although a scenario approach can enable the decision makers to better understand uncertainties and their impacts associated with different future alternatives, how to exactly quantify these uncertainties to achieve perfect confidence in decision making remains an outstanding question. Likewise, although sensitivity and uncertainty analyses are possible within individual modeling systems, the loose coupling between models of different resolutions as outlined in Fig. 2 makes it difficult to achieve cohesive, systematic testing of the entire integrated system desired for establishing credibility among stakeholders and decision makers (e.g., Nguyen and de Kok, 2007; Nguyen et al., 2007). Also, integrated modeling on coupled human-environment systems for decision support is still a poorly developed area, not only in the sense that it is not yet mature enough for decision support systems, but also because that it has yet to provide adequate representations of the dynamics concerning the complex interactions between human and environmental components. Further, successful decision support depends on active and continuous communication and collaboration between stakeholders and researchers throughout the lifetime of the project, which requires a significant investment of time and other resources from both parties that might not be possible or affordable. Finally, although involving the stakeholders and decision-makers in the entire process of model development, implementation, and analysis can help enhance the transparency and credibility of the modeling results, there might still exist additional limitations of decision-makers not selecting a scenario due to political or other concerns/considerations.

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