Multi-resolution integrated assessment and modelling of climate change impacts on water resources in arid and semiarid regions

THORSTEN WAGENER[1], YUQIONG LIU[2], HOSHIN V. GUPTA[2], EVERETT SPRINGER[3] & DAVID BROOKSHIRE[4]

1 *Department of Civil and Environmental Engineering, Pennsylvania State University, 226B Sackett Building, University Park, Pennsylvania 16802, USA*
thorsten@engr.psu.edu

2 *Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona 85721, USA*

3 *Atmospheric, Climate and Environmental Dynamics Group, Los Alamos National Laboratories, MS J495, Los Alamos, New Mexico 87545, USA*

4 *Department of Economics, University of New Mexico, MSC05-3060, Albuquerque, New Mexico 87131-0001, USA*

Abstract Approximately one-third of the Earth's land surface is considered to be arid or semiarid. The availability of water in such regions is particularly sensitive to climate variability while the demand for water is experiencing an explosive increase as populations continue to grow. The competition for available freshwater is exerting considerable pressure on the management of available water resources. If basin-scale water sustainability is to be achieved, managers must somehow attain a balance between supply and demand among the various users throughout the basin, not just for the basin as a whole. The complexity of the interactions between the natural hydrological system and the human environment leaves modelling as the best mechanism for integrating new knowledge into the decision-making process. To this end, the NSF Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) is in the process of developing a multi-resolution integrated modelling framework for the Rio Grande basin in the southwest USA. This paper presents a blueprint of the modelling framework in the context of integrated assessment, describes achievements so far and discusses the science questions which the framework will address.

Key words climate variability; integrated assessment; multi-resolution modelling; Rio Grande, USA; semiarid; water resources management;.

INTRODUCTION

About one-third of the Earth's land surface can be classified as arid or semiarid, with precipitation of less than 250 mm year^{-1} or between 250 and 500 mm year^{-1}, respectively. These areas are particularly sensitive to climate variability, while their populations are growing rapidly (mainly through migration), and are therefore threatened by water shortages. This results in considerable stress on the limited water resources in rivers and aquifers and a strong competition about this limited supply.

The southwestern USA, i.e. the area from New Mexico to California and from Arizona to Utah, is largely semiarid. It has been experiencing a period of drought aggravated by the highest population growth in the USA, partially due to immigration from Latin America and the Far East. The population growth in Nevada, Arizona, New

Mexico and Colorado by far exceeded the national average for the USA over the last 5 to 10 years, and predictions for the next 20 years suggest an almost linear continuation of this trend. Competition for water resources in this area stems mainly from agricultural, urban and in-stream usages. This has led to an overdraft of groundwater, resulting in subsidence problems, and disappearance of much of the riparian habitat.

Basin-scale water sustainability requires that water managers achieve a balance between supply and demand throughout the basin, not just for the basin as a whole. The need to move water around basins to achieve this balance has created the stimulus for water transfers and water markets, and a demand for accurate hydrological information to sustain such institutions (Matthews *et al*., 2002; Brookshire *et al*., 2003; Krause *et al*., 2003). Viable interventions to achieve sustainable management will entail unprecedented coordination across a broad range of disciplines (natural & social sciences).

Integrated assessment is a field that deals with multi-facetted problems of the kind described above in a multi-disciplinary setting. This paper describes an integrated assessment and modelling framework particularly designed for management of water resources in the southwestern USA but sufficiently flexible to be transferable to regions with similar climatic settings. The research is being performed by the Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA; www.sahra.arizona.edu) under funding by the US National Science Foundation. The mission of the Center is to enhance sustainability of water resources in semiarid regions by informing water management and policy. SAHRA conducts multi-disciplinary activities, including research, education and knowledge transfer, to actively create an effective mechanism for rapidly moving the state-of-art science into widespread usage for water resources management. The Center is a partnership of numerous universities, federal, state and local agencies, and non-profit organizations, predominantly located in the southwestern USA.

INTEGRATED ASSESSMENT AND MODELLING

Real world problems, such as that of achieving sustainable basin-scale water management, are highly complex primarily due to the large number of conflicting interests. Recognizing that coordination of multiple disciplines is required if viable intervention strategies are to be achieved, integrated assessment (IA) seeks to combine the socio-economic, environmental and institutional dimensions of a problem (Fig. 1). An IA approach is most commonly implemented by means of an integrated modelling system that combines components from the different disciplines involved and communicates the results of the analysis to decision or policy makers (Hisschemoeller *et al*., 2001; Rotmans & van Asselt, 2001). Modelling provides the mechanism for rapidly bringing the best science into widespread usage for management of water resources, thus bridging the gap between researchers and water resources practitioners. Hisschemoeller *et al*. (2001) list several advantages of using models for IA: potentially providing internal consistency, offering the possibility for formal sensitivity, robustness and uncertainty analysis, and transferability. In their opinion, the main disadvantages are that only well defined systems/cases can be properly analysed, that the parts of the IA framework that do not refer to the environmental system are more difficult to implement (e.g. social behaviour, political structures), and that *continuous intuition checks* are difficult to implement into computer code.

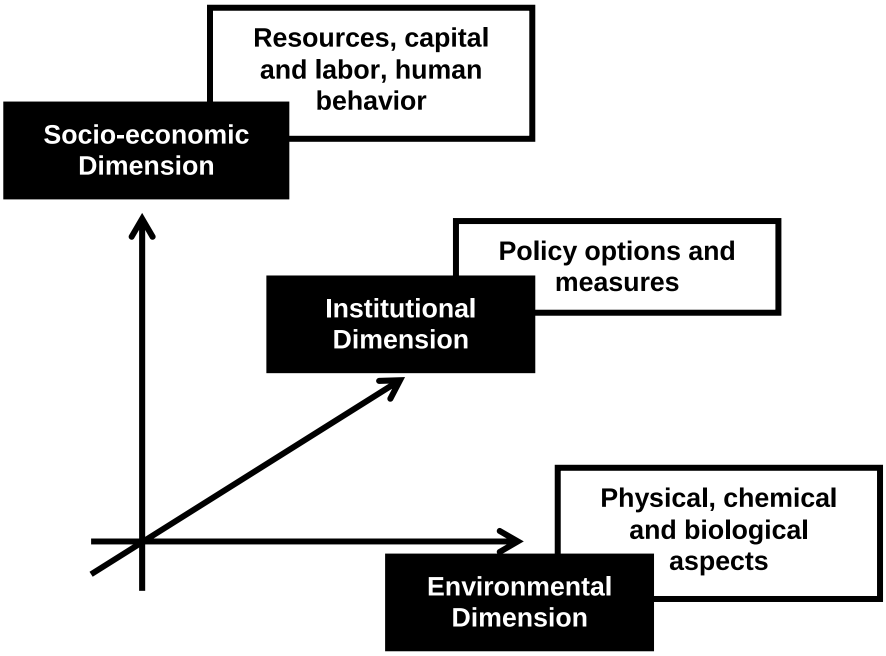

Fig. 1 Dimensions of an integrated assessment problem.

Rizzoli & Young (1997) suggest that an IA tool should possess two main components, one for the storage and processing of data, and one for the interaction with the user. The tool should enable the strict separation of measured information (data) from information created using models. In IAs a GIS is often used due to its strengths when dealing with spatially distributed data. At the same time the IA tool should provide assistance at each of the different stages of usage: (1) during problem formulation and model set-up, (2) during diagnosis, planning, management and/or optimization of the system under study, and (3) by providing the user access to expert knowledge stored or created in the IA tool.

These requirements create the need for a modelling framework that is capable of dealing with data and processes at different spatial and temporal scales. Differences in scale are usually present between the processes of a certain discipline, e.g. a hydrological model of water movement in the basin, but, maybe even more important is the fact that the boundaries of the models required for the different sub-disciplines often do not coincide (Letcher *et al.*, 2004).

The second major issue is complexity. The objective of IA is usually to assess the consequences of questions of policy. IA tools, however, typically show a much larger breadth than depth, with more focus given to combining relatively simple modelling components than to the scientific rigor of individual models. This is usually due mainly to a requirement that the overall modelling framework be able to run quickly on a computer so that stakeholders can interact and communicate with the system in real time (Beek, 1997). In general, this modelling process can be likened to the human thinking process—in our thinking, we typically simplify reality until we can understand individual elements and their connections, in modelling; we simplify reality so we can represent it using mathematical equations. Only if the level of complexity in the model is similar to the level of complexity the user can comprehend will he or she be able to understand the model. This level will of course vary with the technical skill of the user and might be rather low for certain stakeholders or policy makers. In practice, there is therefore some trade-off between the number of components that are built into the system and the level of detail included in individual model components. Of course, the modelled representation of the real world has to be sufficiently realistic for decision makers or stakeholders to accept the validity of the results. This key aspect, the establishing of model credibility in the eyes of decision makers and stakeholders is extremely important, particularly when the model provides results that seem counter-intuitive (Dowlatabadi, 1995).

A further aspect to be addressed in integrated assessment and modelling is that of uncertainty. While individual scientists may be aware of the uncertainties in their particular sub-models, the combined effects of these uncertainties arising from feedbacks between sub-systems is usually poorly understood. Letcher *et al*. (2004) stress the fact that calibration and/or validation data often do not exist to help condition or evaluate the response of the integrated system. Such lack of data is common even for the subsystems. For example, models of watershed behaviour rarely provide reliable predictions without first being tuned using calibration data (e.g. Sivapalan, 2003). The consideration of uncertainty is of particular importance when "what-if" scenarios are to be examined. The level of confidence that can be attached to the model predictions is an important consideration in this context, particularly since calibration data are by definition not available for those cases.

AN INTEGRATED ASSESSMENT APPROACH FOR (SEMI-)ARID REGIONS

The southwestern USA study area

The SAHRA study area encompasses four large watersheds in the southwestern USA: the Upper Rio Grande, the Rio Conchos, the Upper San Pedro and the Salt Verde (Fig. 2). An extensive description of the project area is omitted here due to limitations of space. However, it should be noted that the water in each of these rivers is typically used many times over and that the quality becomes unpotable well before the rivers reach the ocean.

Three water-related issues have been deemed to be of particular importance to support sustainable water resources management in this part of the southwestern USA (Gupta *et al*., 2004), they are:

1. an extensive ongoing landscape transition from historical grassland to shrub land,
2. a continued loss of riparian habitat and invasion by non-native species such as tamarisk (salt-cedar),
3. the need for mechanisms for effective and efficient allocation of water among competing uses, while maintaining appropriate checks and balances to prevent lasting and irreversible environmental damage.

Critical knowledge gaps being addressed by SAHRA to investigate the issues listed above include improved snowpack and rainfall estimates, the role of vegetation type and structure in controlling surface runoff and groundwater recharge, delineation of

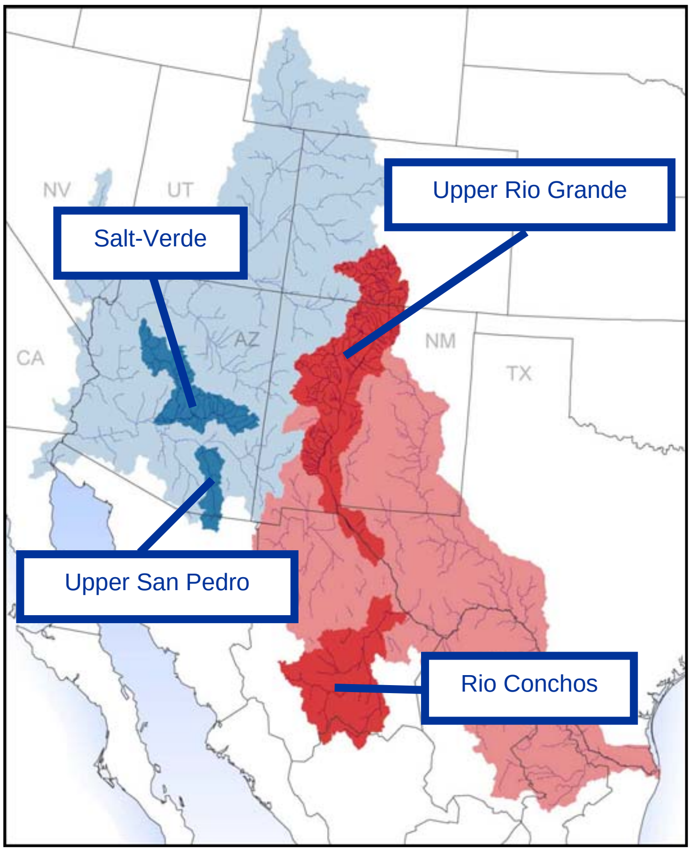

Fig. 2 SAHRA study area in the southwestern USA.

groundwater recharge rates, water–nutrient–vegetation interaction in riparian zones, and the behavioural factors that control urban demand (Gupta *et al*., 2004).

In the next section, we discuss how the general requirements for an IA and modelling tool combine with the specific requirements dictated by the study area, leading to the approach selected for this project.

Integrated assessment and modelling in SAHRA

The first step in developing an IA modelling system is for a group of diverse scientists to come together with a common goal. During this initial phase considerable time is spent overcoming differences in language and terminology, as well as in background and experience. Janssen & Goldsworthy (1996) stress the importance of the development of common norms and values in this context. In SAHRA, this step was (and continues to be) facilitated through the development of a common conceptual (sometimes termed perceptual) model of the study area.

Further integration and a narrowed focus are subsequently achieved through a basin focus (outlined above) and via scenario analysis. A scenario that integrates the three water-related issues listed above, as well as the problems of climate variability and population growth, is to simulate the effects of a 1950s type drought (the severest in the last 100 years) on the water balance of the basin, using 1990s population and land use. This scenario allows for the integration of scales, disciplines, models and even stakeholders as required in an IA context. Three critical relevant science questions that have to be addressed are:

1. What are the impacts of (decadal-scale) vegetation change on basin-scale water balances?
2. What are the (physical, ecological and economic) costs and benefits of riparian preservation and/or restoration?
3. How can water markets or water banking be implemented in the semiarid southwestern USA?

A modelling system developed to answer these questions must satisfy diverging and sometimes even contradicting requirements. This is particular obvious with respect to the selected complexity of the modelling tools used in the system. On the one hand, the system must be easily understood by stakeholders and able to run in real-time to facilitate interaction. On the other hand, it must contain sufficient physical rigor and detail to be able to properly address complex questions. For these reasons, systems with varying degrees of complexity have been developed (HarmoniT, 2002). Letcher *et al*. (2004) advocate an approach that begins with simple models and progressively adds complexity based on stakeholder needs. This approach is in line with the top-down modelling philosophy applied in a variety of fields (e.g. Young, 2003).

The approach chosen by SAHRA to address the issues of scale, credibility and communicability is a multi-resolution modelling framework (Fig. 3). It consists of models at fine (100 m), medium (1–12 km) and coarse resolution (sub-watershed). Each resolution offers specific advantages and disadvantages, but the strength of the approach lies in the connection and consistency between them.

The coarse resolution model is build using a systems dynamic modelling environment and is intended for decision support with a focus on communicability and ease of understanding. It is therefore ideal for higher level scenario analysis, public outreach and education. Its spatial resolution is based on US Geological Survey gauge locations and the connection points of an existing water allocation model. It allows for the incorporation of human population growth and the economic evaluation of water uses.

The medium resolution modelling component is based on a combination of land-surface–atmosphere water and energy balance models. This type of model commonly uses a grid-based representation of the basin with cell sizes varying between 1 km and 12 km. Engineering structures such as water controls and irrigation channels, as well as behavioural (economic) components will be explicitly included at this level.

The fine resolution component consists of coupled high-resolution atmosphere–surface–subsurface water and energy balance models, with 1–5 km grids for the atmosphere, 100 m grids for the land surface, and a variable resolution for the subsurface. This resolution component is based on a rigorous bottom-up (mechanistic) approach to the modelling of physical systems.

The IA modelling framework therefore ranges from components at high resolution with great physical rigor to components that are easy to understand, run and communicate. In practice, such an approach can only be successful if a great degree of both internal consistency among different modelling components and external consistency with the physical system is present. While the common underlying conceptual model can ensure a certain degree of qualitative consistency, a quantitative analysis must also

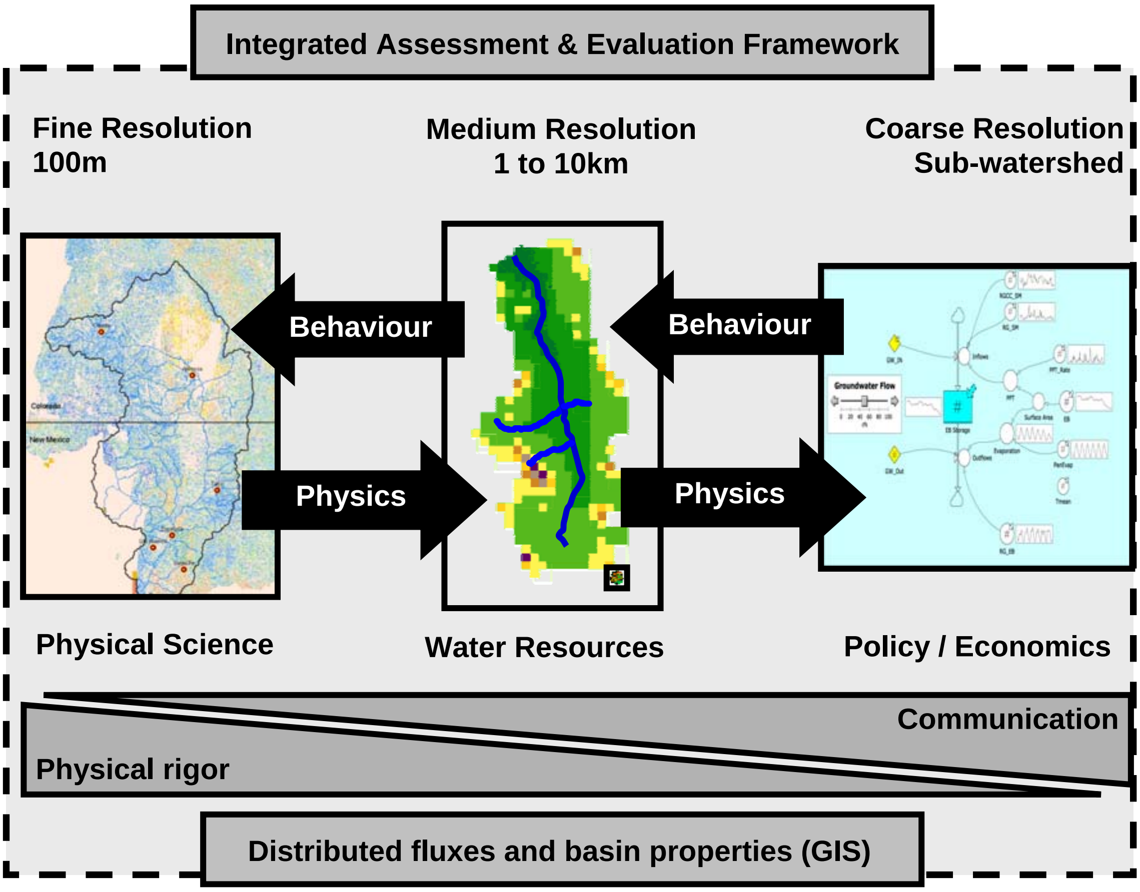

Fig. 3 SAHRA integrated assessment and modelling framework.

be conducted through an evaluation framework and a web-based geo-spatial database, the latter to store and manage the various vector and raster data such as distributed fluxes, basin properties, and modelling outputs. This allows a comprehensive evaluation of the consistency between mass fluxes at different levels of resolution, as well as the consistency between model outputs and measurements of water and energy fluxes in the basin.

CONCLUSIONS AND OUTLOOK

For SAHRA to achieve its vision of impacting water resources policy and management, we must demonstrate success in achieving a viable and credible integrated assessment and modelling framework/decision support system as a fundamental vehicle for bringing scientific understanding to bear on the decision making process. Eventually this integrated modelling framework will be available to assess impacts of climate variability and land use change on water resources in semiarid river basins around the world.

Acknowledgements Support for this work was provided by the National Science Foundation Science and Technology Center on “Sustainability of semi-Arid Hydrology and Riparian Areas" (SAHRA) (EAR-9876800). The first author also gratefully acknowledges support from the German Academic Exchange Service (DAAD) through its post doctorate fellowship program.

REFERENCES

Beek, E. van (1997) Integrated water management course – Part II. Lecture Notes, Department of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands. Unpublished.

Brookshire, D. S., Burness, S. & Chermak, J. (2002) Western urban water demand. *Natural Resour. J*. **42**(1).

Dowlatabadi, H. (1995) Integrated assessment models of climate change: An incomplete overview. *Energy Policy* **23**, 289–296.

Gupta, H. V., Brookshire, D., Springer, E. & Wagener, T. (2004) Multi-resolution integrated modeling for basin-scale water resources management and policy analysis. In: *British Hydrological Society Symposium Proceedings* (London, July 2004), 392–397.

Hadjigeorgalis, E.& Lillywhite, J. (2004) The impact of institutional constraints on the Limarí River Valley water market. *Water Resour. Res*. **40**(5), W05501, doi:10.1029/2003WR002701.

HarmoniT (2002) State of the art review – Work package 1. HR Wallingford Reports SR 598. Unpublished.

Hisschemoeller, M., Tol, R. S. J. & Vellinga, P. (2001) The relevance of participatory approaches in integrated environmental assessment. *Integrated Assessment* **2**, 57–72.

Jakeman, A. J. & Letcher, R. A. (2003) Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling & Software* **18**, 491–501.

Janssen, W. & Goldsworthy, P. (1996) Multidisciplinary research for natural resource management: conceptual and practical implications. *Agric. Syst*. **51**(3), 259–279.

Krause, K., Chermak, J. & Brookshire, D. S. (2003) The demand for water: consumer response to scarcity. *J. Regulatory Econ*. **23**(2), 167–191.

Letcher, R. A., Jakeman, A. J. & Crok, B. F. W. (2004) Model development for integrated assessment of water allocation options. *Water Resour. Res*. **40**, W05502, doi:10.1029/2003WR002933.

Matthews, P. L., Scuderi, D. S., Brookshire, D. S., Gregory, K., Snell, S., Krause, K., Chermak, J., Cullen, B. & Campana, M. (2001) Marketing western water: can a process based geographical information system improve reallocation decisions? *Natural Resour. J*. **41**(2).

National Drought Mitigation Center (NMDC) (2003) What is drought? http://www.drought.unl.edu/whatis/concept.htm Accessed September 2003.

Parker, P., Letcher, R., Jakeman, A., Beck, M. B., Harris, G., Argent, R. M., Hare, M., Pahl-Wostl, C., Voinov, A., Janssen, M., *et al*. (2002) Progress in integrated assessment and modeling. *Environmental Modelling & Software* **17**(3), 209–217.

Reed, M., Cuddy, S. M. and Rizzoli, A. E. (1999) A framework for modelling multiple resource management issues—an open modelling approach. *Environmental Modelling & Software* **14**(6), 503–509.

Rizzoli, A. E. & Young, W. J. (1997) Delivering environmental decision support systems: software tools and techniques. *Environmental Modelling & Software* **12**(2–3), 237–249.

Rotmans, J. & van Asselt, M. B. A. (2001) Uncertainty in integrated assessment modelling: a labyrinthic path. *Integrated Assessment* **2**, 43–55.

Sivapalan, M. (2003) Prediction in ungauged basins: a grand challenge for theoretical hydrology. *Hydrological Processes – HP Today* **17**(15), 3163–3170.

Young, P. C. (2003) Top-down and data-based mechanistic modeling of rainfall-flow dynamics at the catchment scale. *Hydrol. Processes* **17**, 2195–2217.