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Multi-Resolution Integrated Modeling For Basin-Scale Water Resources Management and Policy Analysis

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Introduction

Approximately one-third of the land surface of the Earth is considered to be arid or semi-arid with an annual average of less than 12-14 inches of rainfall. The availability of water in such regions is of course, particularly sensitive to climate variability while the demand for water is experiencing explosive population growth. The competition for available water is exerting considerable pressure on the water resources management. Policy and decision makers in the southwestern U.S. increasingly have to cope with over-stressed rivers and aquifers as population and water demands grow. Other factors such as endangered species and Native American water rights further complicate the management problems. Further, as groundwater tables are drawn down due to pumping in excess of natural recharge, considerable (potentially irreversible) environmental impacts begin to be felt as, for example, rivers run dry for significant portions of the year, riparian habitats disappear (with consequent effects on the bio-diversity of the region), aquifers compact resulting in large scale subsidence, and water quality begins to suffer. The current drought (1999-2002) in the southwestern U.S. is raising new concerns about how to sustain the combination of agricultural, urban and in-stream uses of water that underlie the socio-economic and ecological structure in the region.

The water stressed nature of arid and semi-arid environments means that competing water uses of various kinds vie for access to a highly limited resource. If basin-scale water sustainability is to be achieved, managers must somehow achieve a balance between supply and demand throughout the basin, not just for the surface water or stream. The need to move water around a basin such as the Rio Grande or Colorado River to achieve this balance has created the stimulus for water transfers and water markets, and for accurate hydrologic information to sustain such institutions [Matthews et al. 2002; Brookshire et al 2003; Krause, Chermak Brookshire, 2003].

What is SAHRA

SAHRA is a Science and Technology Center funded by the US National Science Foundation (NSF) under a ten year grant (2000-2009) to conduct integrated multi-disciplinary activities designed to actively bridge the gap between research and the tools used by water resources policy makers and managers (www.sahra.arizona.edu). The driving question behind SAHRA is "How can science help communities to manage their water resources in a sustainable manner". Clearly, the power to improve the sustainability of water resources properly rests with elected officials, professional water managers, and legal experts. SAHRA's purpose is, therefore, to inform and support water professionals by conducting stakeholder-relevant natural and social science research, education and knowledge transfer activities. The Center itself is based at the University of Arizona (UA) in the Department of Hydrology and Water Resources, and involves partnerships with numerous universities, federal, state and local agencies, and non-profit organizations.

Because key within-basin fluxes of water are poorly known, and given the strong physical-social interactions that influence basin-scale water cycles, the SAHRA integrated research agenda is designed to identify and address critical knowledge gaps, including (for example) snowpack and rainfall estimates, the role of vegetation type and structure in controlling surface runoff and groundwater recharge, delineation of groundwater recharge rates, water-nutrient-vegetation interactions in riparian zones, and the behavioral factors that control urban water demand. Important indicators of success for SAHRA are an increased demand for improved hydrologic information for water resources decision making, a research agenda that both advances the science and is responsive to stakeholder needs, research team integration and quality, and frequent researcher-stakeholder interactions.

Further, because the success of any water resources policy or management ultimately depends on the degree of hydrologic literacy of the public, SAHRA's education agenda includes building an understanding of key water issues into K-16 science education. The center has therefore worked to define the components of basic hydrologic literacy, including measurements of baseline levels, and is engaging in a coordinated set of activities to increase hydrologic literacy, not only at the K-12 level, but throughout the population that makes water use and related political decisions.

Finally, bridging the gap between research and practice depends on the success with which new knowledge find its way from the research arena into the technological skill set of the professional communities that develop and implement water resources policy and manage our water resources. Consequently SAHRA's knowledge transfer efforts seek to build bi-directional channels of communication via both active and passive mechanisms such as web-sources [e.g., the *Water News Watch:* www.sahra.arizona.edu/newswatch/; and the *Hydroarchive* software exchange site: www.sahra.arizona.edu/software/], a Trade magazine [Southwest Hydrology Journal], and active dialogues through which the needs of a wide spectrum of stakeholders are incorporated into our science agenda.

SAHRA Focus & Methods

SAHRA has two main foci, a) creating new knowledge, and b) building understanding. The major portion of the center's activities is conducted within four relatively large sub-basins in the Southwestern US, the Upper Rio Grande, the Rio Conchos, the Upper San Pedro, and the Salt Verde (Figure 1), in the region of the US-Mexico border. New knowledge is being created by selective funding of a number of creative multi-disciplinary science tasks aimed at helping to answer a targeted set of scientific questions perceived to be critical to these basins. The natural science activities are grouped into tasks that seek to understand a) medium- to long-term basin scale water and nutrient balances with particular attention to the role played by vegetation, and b) river system riparian plant-water-nutrient interactions. Both of these draw upon the expertise of a wide range of disciplines including hydrologists, ecologists, geologists, geochemists, behavioral scientists and economists. The intention is for the understanding developed by these activities to be disseminated to professionals and the public, but also to be integrated into computer-based mathematical modeling systems that can be used for policy analysis and decision making.

Coordination of the science activities of SAHRA is achieved by the selection of a limited set of integrating science questions developed in collaboration with stakeholders and in response to the primary issues currently faced by water resources decision makers and therefore also in the public eye (via the media). The current set of three questions is: 1) What are the impacts of decadal scale vegetation changes on basin scale water balances? 2) What are the costs and benefits of riparian preservation/restoration? and 3) How can water markets and water banking be implemented? You may notice that both economics and the role of water-vegetation interactions currently take center stage.

The first question is motivated by the fact that there is an ongoing and extensive transition from historically grassland landscapes to shrub land in the southwestern US. Some ranchers and landowners perceive the "invasion by water hungry plants" to be "robbing our aquifers, streams and rivers of that life giving resource ... using up to half of our annual precipitation", and champion action to remove the shrubs, under the idea that this will enhance water recharge and storage. Others recommend thinning the forests, again with the view that this will reduce evapotranspiration. Scientists and decision makers are therefore interested in knowing whether and how changes in vegetation might affect the dynamics and magnitudes of runoff and groundwater recharge, and whether controlling or altering vegetation type is likely to lead to decreased risk of fire, improved water quality and/or an overall increase in water availability.

The second question is motivated by the fact that as groundwater pumping draws down the water table and as river management strategies modify the hydrologic environment in the rivers, riparian habitats are either being lost or being invaded by non-native species such as tamarisk (salt-cedar). The latter species was introduced approximately 150 years ago as a mechanism to control erosion, but is able to out-compete native species under the modified hydrologic regimes and is now widely perceived as being a water thirsty "weed". Given current concerns about widespread drought (and, in New Mexico, the need to meet its Federally mandated compact delivery requirements to Texas), there is considerable political interest in implementation of measures to remove tamarisk. Scientists and decision makers are therefore interested in knowing whether and how such riparian restoration would actually result in water savings and overall improvement to the health of the river system environment (including animal and bird habitats). In a related question, and in response to strong environmental concerns among the public, decision makers are interested in knowing what minimum water levels must be maintained in the riparian system to meet the needs of vegetation and wildlife.

The third question is motivated by the need for more effective and efficient mechanisms for determining how to allocate water among competing uses, while maintaining appropriate checks and balances to protect the environment from lasting and irreversible damage. Given the political and legal complexities of water rights, some economists have proposed that water markets and/or water banking could be used to improved water use efficiency without involving significant oversight by the government [Brookshire, 2003, Brookshire et al 2003 and Mathews et al 2002]. One emerging view is that water banks and marketing are essential to minimizing water crises in critical areas of the southwestern U.S. [US Department of Interior, 2003]. Scientists and decision makers are therefore interested in using detailed integrated modeling to explore how potential water markets might work, and how pricing and/or water conservations efforts might influence consumption.

Integrated Multi-Resolution Modeling

Water, being the source of life, lies at the heart of much of human endeavor, and consequently figures centrally in the politics of any semi-arid region. The tremendous complexity of the interactions between the natural hydrologic system and the human environment is driving the practice of water resources management towards an Integrated Assessment (IA) approach which includes environmental, social and economic values into the decision making process [Jakeman and Letcher, 2003]. This involves the use of inter-disciplinary science (including elements of the natural and human sciences) to analyze complex, real world, situations and problems at multiple temporal and spatial scales, and to communicate the knowledge gained to decision and policy makers.

One of the few available IA mechanisms for properly integrating new knowledge into the decision making process is computer-based modeling [Hisschemoeller *et al.*, 2001]. Models are useful, because people think and communicate in terms of models as simplifications of reality [Jakeman and Letcher, 2003]. Basin-scale integrated models have the potential to allow us to study the feedback processes between the physical and human systems, including economic, institutional, engineering, and behavioral components [Rotmans and van Asselt, 2001], so that potential second- and higher-order effects of political and management decisions can be investigated and used in the selection of rational water-resources policy. Hisschemoeller *et al.* [2001] list the advantages of using a model for IA as potentially providing internal consistency, the possibility for formal sensitivity, robustness and uncertainty analysis, and transferability. Disadvantages include the facts that only well defined problems can be properly analyzed, the parts of the integrated model that do not refer to the environmental system are more difficult to implement (e.g. social structure, politics), and *continuous intuition checks* are difficult to implement into computer code. Nonetheless, it is clear that integrated basin model have the potential ability to serve as the repository of current best available knowledge about the system, and can be used to generate simulations of the probable effects of human actions while taking into account the uncertainties brought about by future climatic variability. While water allocation and usage policies are necessarily political decisions, the strength of these policies depends critically on the quality and completeness of the knowledge that is used to inform the decision making process. We envision that, in the not so distant future, decision makers would be able to call upon a designated basin modeling authority and request that simulations be generated to investigate the behavior of the water resources system under particular scenarios of interest, to explore feasibilities, costs and benefits (both market and non-market) and to identify interactions and feedback effects that need proper consideration (Figure 2).

With this vision in mind, SAHRA is pursuing a modeling strategy that includes three overlapping resolutions – coarse, medium and fine (Figure 3). The coarse resolution modeling approach (CRM), with leadership by Sandia National Laboratories (SNL), treats the basin as composed of a hierarchical system of lumped and overlapping units (hydrological, political, economic, engineering, etc.) constructed within a graphical user environment that readily facilitates the rapid, albeit crude, analysis and exploration of dynamic system responses to user selected perturbations. The finest spatial resolution is coordinated to be consistent with the USGS (United States Geological Survey) streamflow gage locations, and the time step is one month. The system is being implemented within the PowerSim© environment (www.powersim.com) and can be run on personal computers.

The fine resolution modeling approach [FRM; Winter et al. 2004], conducted by the hydrologic sciences team of the Los Alamos National Laboratory (LANL), involves a highly detailed grid-based representation of the physics of the water and energy balance of the atmosphere-land-groundwater hydrologic system, implemented on a massively parallel super computer having 2048 nodes. Because of the focus on hydrologic processes on and within the ground, the land surface is modeled at a spatial grid resolution of 100 meters, with atmospheric fluxes downscaled from an atmospheric model component running at 5 km grid resolution. The very fine resolution of the land surface component is designed to facilitate the incorporation of knowledge gained from plot-scale experiments, so that a) the model simulations can actually be evaluated against small scale measurements made on the ground, and b) the effects of scaling processes up from plot to larger scales can be properly investigated. This unique project is clearly a high-risk and massive undertaking, and is being conducted to explore the possible future potential and relevance of bottom-up modeling to resource management. Certain kinds of policy questions, such as questions regarding the possibility of water allocation strategies to preserve and maintain environmentally endangered species such as the currently threatened "snail darter" fish in the Rio Grande, may only be addressable using government supported modeling initiatives of this magnitude and scope.

Finally, the medium resolution modeling approach (MRM), led by scientists at the UA and USGS, splits the difference between the fine and coarse resolution strategies. The spatial resolution of the model is designed to be variable, ranging from 1 to 10 km grid sizes depending on practical considerations and the need for detail, and the time step is one hour. This model facilitates a compromise between the need for detailed representation of the physics of the system and the need to couple model components representing the water engineering control structures (reservoirs, inter and intra-basin transfer projects, irrigation canals, wells, etc.) and behavioral processes (economic and legal institutions, population responses, etc.). The model is being implemented on a commercially available multi-node Linux-based Penguin computing cluster located at the UA.

The three-resolution modeling strategy represents an attempt to coordinate and focus the efforts of a large and diverse group of physical and social science researchers while acknowledging the variety and complexity of factors and components involved in water resources decision making. The entire modeling framework rests upon an evolving "conceptual/perceptual" model of the river basin, which reflects our current (albeit steady state) understanding of the important hydrogeology, ecology, engineering, and behavioral processes and their interconnections within the system (Figure 4). The idea is that hydro-eco-geologic knowledge gained in the field can be incorporated into detailed representations of the physics within the FRM, which can be used to generate appropriate parameterizations at the coarser (1-10 km) scale more appropriate for practical decision support. Similarly, the equations representing hydrologic processes at the lumped CRM scale can be selected to be consistent with the aggregate process behavior simulated by the intermediate MRM. Conversely, the CRM facilitates practical initial development and testing of lumped versions of the behavioral (economic, institutional, etc.) model components used to guide later more detailed implementations within the MRM.

Final Comments

The success of SAHRA in achieving its vision of positively impacting water resources policy and management is likely to depend in large measure on our success in demonstrating the viability of integrated modeling as a fundamental vehicle for bringing scientific understanding to bear on the decision making process. The modeling strategy described above has evolved slowly over the past four years as we have sought to understand the challenges faced by decision makers and the strengths and weakness of the modeling tools currently at our disposal. Even more important, the past four years has involved a slow but steady process of mutual education in which physical scientists, behavioral scientists, and modeling scientists have struggled to understand each other's language and particular points of view. By the end of the third year of SAHRA activity, the common framework outlined here had emerged and the modeling teams are now actively engaged in the initial phases of model development. By the end of the fifth year, we expect to have begun coordinated cross model comparisons and evaluations, so as to better understand the demands of inter-model information exchange, and to explore the strengths and limitations of the three-resolution strategy. We also expect to be actively engaged in more specific stakeholder-modeling team dialog so that our stakeholder partners remain active participants with full ownership of the process, thereby being able to provide further refinements to the directions of our science activities. It is our goal that this process will generate a critical level of buy-in among local and regional hydrologic decision makers so that political and financial support for the integrated modeling activity will survive the limited term of seed funding provided by the National Science Foundation.

Acknowledgements

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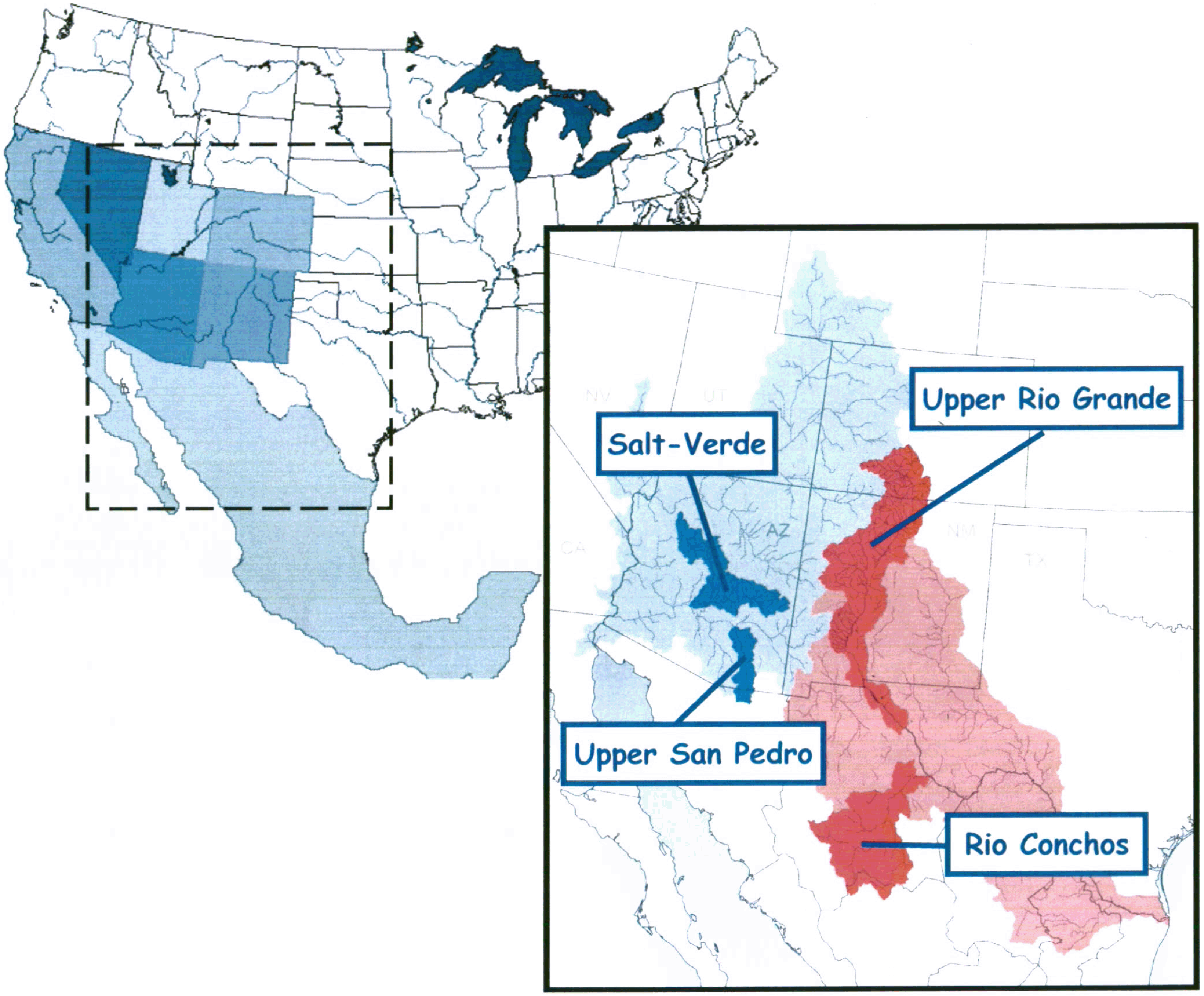

Figure 1: The geographical focus of SAHRA activities

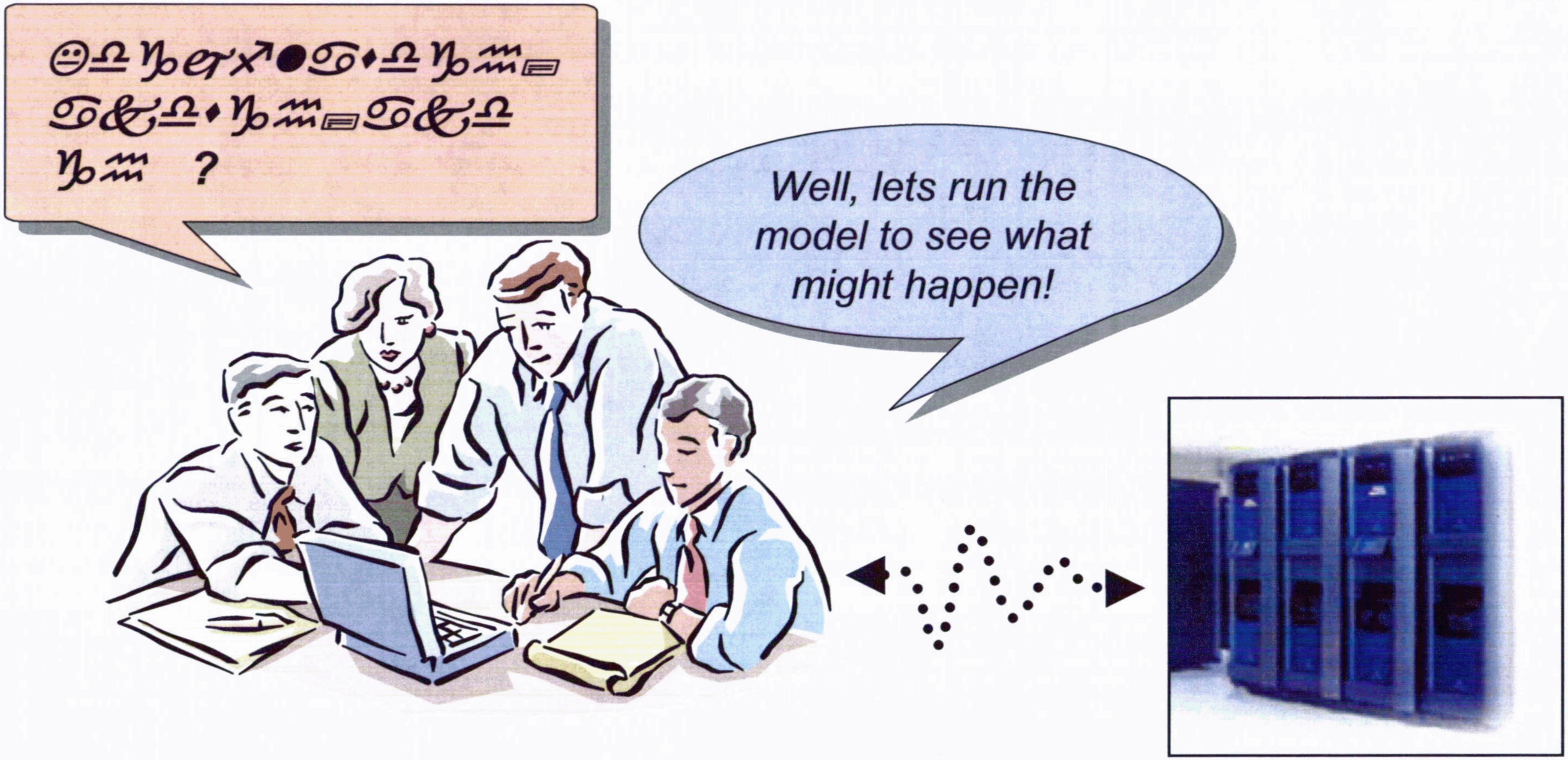

Figure 2: Integrated modeling as a tool for basin hydrologic decision making

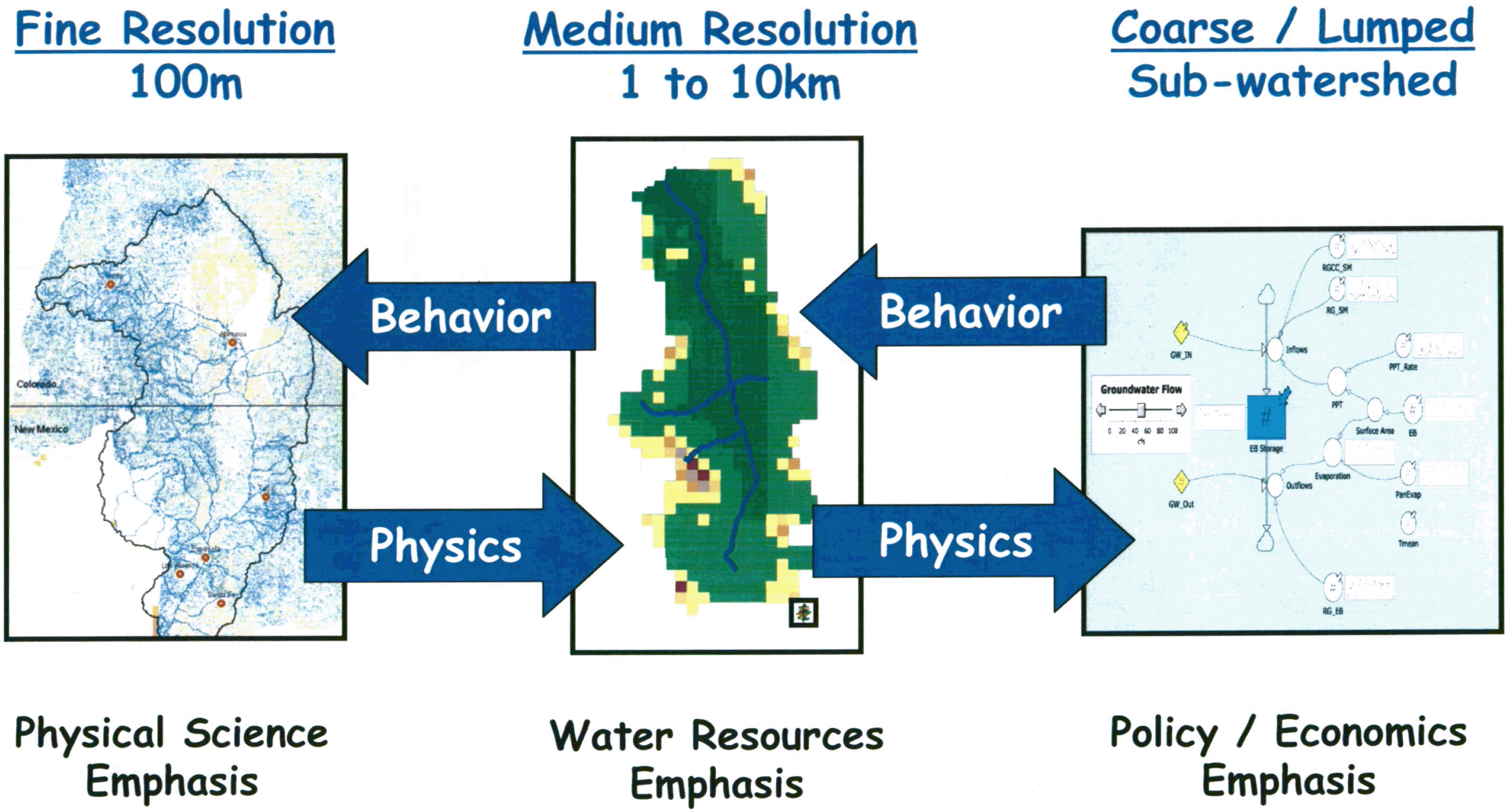

Figure 3: Three overlapping resolution integrated modeling approach

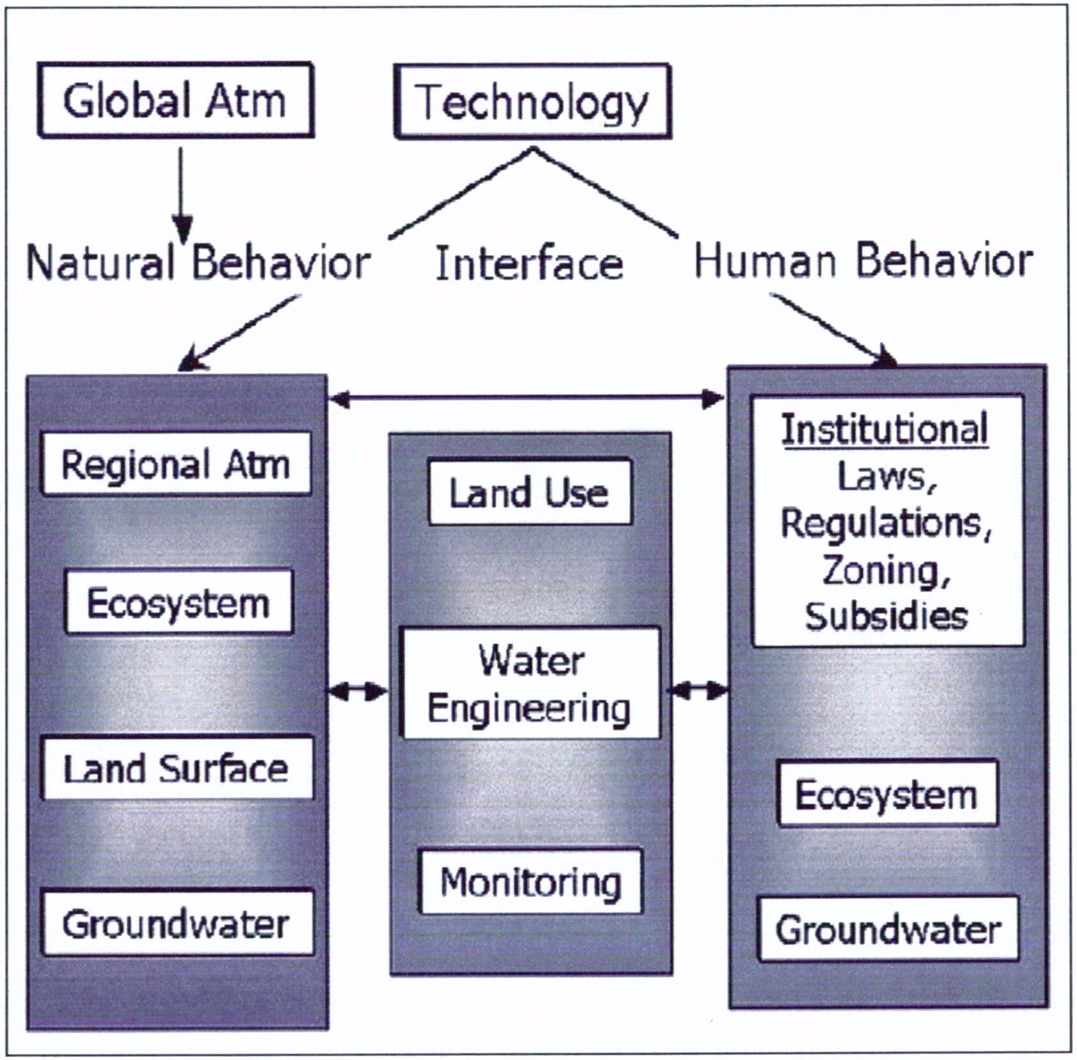

Figure 4: Physical, behavioral & institutional components of an integrated model