Development of an Integrated Hydologic Model to Explore the Feasibility of Water Banking and Markets in the Southwestern U.S.

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EXTENDED ABSTRACT

The American West is the fastest growing region in the United States. It also has a significant portion of the region that is arid and is currently experiencing an extensive drought. The drought may continue for many years to come. Water development in the western U.S. has traditionally been aimed at ensuring water supplies in the face of climatic and anthropogenic change. However, the development of "new" supplies through reservoir development and other infrastructure will no longer be possible. Essentially water that has always been scarce is becoming scarcer. This ever-increasing scarcity is contributing to an increasing number of conflicts between traditional water users such as farmers and ranchers and environmental and recreation users, while urban demand continues to increase. Water 2025: Preventing Crisis and Conflict in the West addresses these issues and calls for the development of water markets and banks for the reallocation of water in order to more efficiently provide water amongst the competing needs. The 2025 U.S. Department of Interior publication calls directly for the development of water markets and banking systems to address the ever-increasing water shortages in the Western U.S.

Researchers at the Desert Research Institute (DRI) are conducting research within the U.S. National Science Foundation (NSF) Science and Technology Center (STC) for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) aimed at developing an integrated physical and engineering hydrologic model for the purpose of investigating the feasibility of water banking and markets in the Rio Grande watershed. The main components of the integrated model include a detailed representation of system behavior in (1) headwater areas (snow accumulation and melt); (2) surface reservoirs and conveyance systems (operational surface reservoirs, river routing, and diversions/returns); (3) regional and near river aquifers; (4) agricultural demand and uses; and, in future work, (5) urban and industrial demand and uses. Existing models of several of these components have been identified and are being included, to some degree, in the initial integrated model. Coupling of existing and new models of each component to create the final completely integrated model requires a detailed understanding of the problem requirements (what questions are being asked) and the data (what information is available in the hydrologic data). Once developed and tested, the integrated model will be used with an economic "Market" model and "Behavior" model to investigate several water market and banking scenarios.

The integrated physical model will need to be sufficiently distributed to allow for the tracking of water movement, possibly at the ditch level for an irrigation district. The model may need to be tightly coupled to account for ground/surface water. Whether, in fact, this needs to be done, will depend on the specific scenarios that are to be tested and explored. The engineering/infrastructure module must represent the capabilities of water movement and storage for the hydrologic setting of the water bank. The institutional module will consist of the legal and regulatory framework. Finally, the economic module will be a trading institution. All of these models must be coupled and interactive for a true water banking system to exist and represent the actual physical hydrology with legal/economic institutions for water resources management.

The linked models will be used to study feedbacks between physical processes, water resources management institutions and economic decisions. Once the component modules are developed and tested, they will be used for scenario analysis, all within the context of water markets and banking as policy solutions to allow for more efficient reallocation of water in semi-arid environments. It is hoped that this effort will represent a significant step for water resources systems, and the experience gained is expected to guide development of more robust interfaces which can inform policy. The work described in this paper represents the current state of the development of the integrated hydrologic model.

1. INTRODUCTION

The primary goal of this project is to develop a medium resolution integrated hydrologic model (MRM) of the Rio Grande basin, including representations of the surface and subsurface hydrology. To date, several components of the MRM have been identified and/or developed for the Rio Grande. The MRM consists of three main modeling components: (1) an existing high resolution (space and time) streamflow generation model of the upper Rio Grande watershed; (2) an existing hydrologic engineering model of the important and relevant operational and river routing features of the upper and middle Rio Grande; (3) an existing high resolution (space) groundwater model of the middle Rio Grande.

The primary challenge of this effort is to integrate different aspects of each of the three existing models to provide an integrated system representation of the hydrologic behaviors of the Rio Grande watershed for future scenario testing and analysis (see Figure 1). The integration, or coupling, will be done within the USGS Modular Modeling System (MMS) and USGS Object User Interface (OUI) modeling framework (Markstrom et al., 2002 and Leavesley et al., 1983).

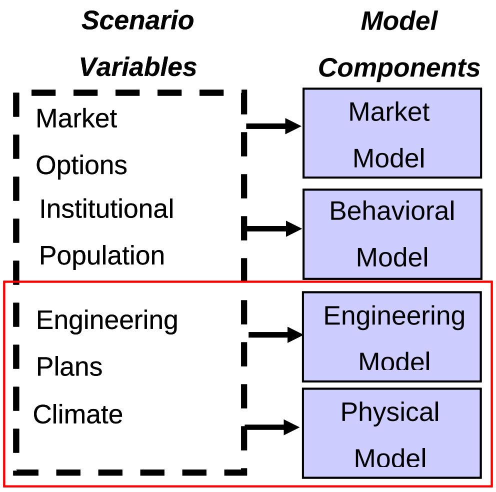

Figure 1. Overview of Water Market and Banking. Red box highlights components described in this paper.

In the following sections, the Rio Grande study area, the three modeling components, and the integrating modeling framework are presented and discussed.

2. RIO GRANDE STUDY AREA

The upper Rio Grande watershed is approximately 83,400 km^2 and ranges in elevation from 1,200m near the New Mexico and Texas border to over 4,250m in the headwater areas in southern Colorado. Nearly one third of the water flowing in the Rio Grande is generated from snowmelt in high-elevation headwaters areas (see shaded watersheds shown in Figure 2). The high-elevation watersheds are mountainous (elevation range is 2,400m to 4,250m), snow-dominated, watersheds in the Rocky Mountains of southern Colorado and New Mexico. The vegetation is predominantly coniferous forests with a mix of alpine tundra and bare rock on areas above timberline.

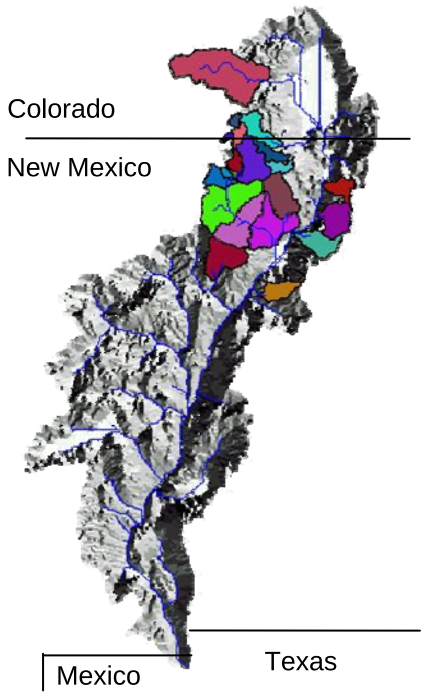

Figure 2. Overview of the upper Rio Grande study area.

The lower, or middle portion of the Rio Grande, is arid and semi-arid land that contains a significant amount of agricultural area primarily along a narrow corridor surrounding the main stem of the Rio Grande. A large number of diversion and returns from the main stem are use to irrigate agricultural areas throughout the middle Rio Grande reach. Groundwater pumping is also a significant source of water for both agriculture and municipal users in the middle Rio Grande.

3. HYDROLOGIC MODEL COMPONENTS

In this section, the existing streamflow generation model, river operations model, and groundwater models are presented.

3.1. Streamflow Generation Model

As part of the U.S. Department of Interior's Watershed and River Systems Management Program (WaRSMP), a streamflow generation model of the high-elevation headwaters areas of the upper Rio Grande was developed using the USGS Precipitation Runoff Modeling System (PRMS) (Leavesley et al., 1983) within the USGS Modular Modeling System (MMS) (Leavesley et al., 1996) as part of the Watershed and River Systems Management Program (WaRSMP). The primary purpose of this model component is to simulate continuous streamflow behavior from mountainous areas of the Rio Grande where snow accumulation and melt dominate the hydrologic processes (see Figure 3). The streamflow output from this model serves as input to the river operations model described in section 3.2.

This MMS-PRMS model was recently expanded by SAHRA researchers to include all of the remaining contributing area of the upper Rio Grande. The MMS-PRMS model is currently running and is being tested for use within the MRM. The surface to groundwater recharge estimates from this model will serve as input to the regional groundwater model described in section 3.3.

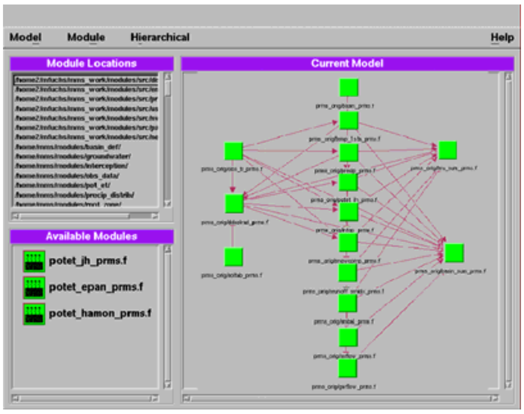

Figure 3. USGS Modular Modeling System.

The PRMS is a distributed-parameter, physical process hydrologic model that allows the user to partition the watershed into hydrologic response units (HRU) based on different characteristics of a watershed (e.g., slope, aspect, stream network, elevation etc.).

In the existing and expanded PRMS models of the upper Rio Grande, the watersheds were partitioned into HRUs based on topography and other important hydrologic characteristics of the watersheds. Daily values of precipitation and mnimum and maximum temperature were estimated for each HRU from October 1988 to present using regional linear relationships between the elevation, latitude, and longitude of the observation sites and the centroids of the HRUs.

Many of the PRMS model parameters were derived directly from spatial information describing important hydrologic characteristics of the watershed (e.g., soils, vegetation, slope, aspect, etc.) using existing empirical relationships. The remaining model parameters were estimated using a manual calibration approach to simulate the observed streamflow at the outlet of each watershed.

3.2. River Operations Model

The Upper Rio Grande Water Operations Model (URGWOM) is a set of daily time-step, river-reservoir models for the Upper Rio Grande basin (see Figure 4) utilizing a numerical computer modeling software (RiverWare). It is capable of simulating the river and reservoir hydrology, water accounting and operation logic in the Rio Grande upstream of Elephant Butte Reservoir in New Mexico, and flood control from Elephant Butte Dam to American Dam near Fort Quitman. The models are currently being tested for use in flood control operations, water accounting, and in the evaluation of short and long-term water-operation alternatives.

The RiverWare routing component of URGWOM requires streamflow hydrograph estimates at many locations throughout the Upper Rio Grande Basin. The MMS-PRMS streamflow forecast model described in section 3.1 is used to estimate daily runoff hydrographs for each URGWOM input location in the basin.

The combined MMS-PRMS and URGWOM models are also used to set flow rates for other operations, such as diversions, wastewater returns, drain flows, precipitation, etc., for use in a water operations and accounting model. In 2005, SAHRA signed the URGWOM Memorandum of Understanding to become an official URGWOM collaborator and was able to obtain the URGWOM planning model for use within the MRM.

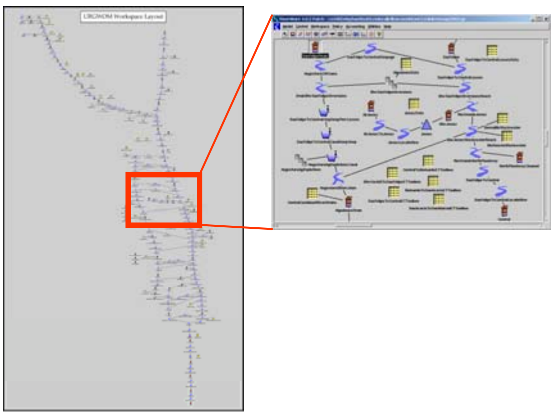

Figure 4. Rio Grande river operations model, URGWOM.

3.3. Regional Groundwater Model

A three-dimensional, finite-difference, ground-water-flow model of the Santa Fe Group aquifer system (see Figure 5) within the middle Rio Grande basin between Cochiti and San Acacia, New Mexico was developed by the USGS (McAda and Barroll, 2002) using the MODFLOW software package to (1) simulate the complex interactions between the surface-water and ground-water-flow systems in the basin and (2) to provide a tool to help water managers plan for and administer the use of basin resources. The model simulates predevelopment steady-state conditions and historical transient conditions from 1900 to March 2000 in 1 steady-state and 52 historical stress periods. The model also simulates the Rio Grande, riverside drains, Jemez River, Jemez Canyon Reservoir, Cochiti Lake, riparian evapo-transpiration, and interior drains as head-dependent flow boundaries. This ground water flow model provides a reasonable representation of the hydrogeologic processes of the basin and simulates many historically measured trends in flow and water levels.

In late 2004 SAHRA contacted the USGS model developers and obtained the model for use within the MRM. The USGS model has been compiled and run within SAHRA and is currently being tested for use within the MRM.

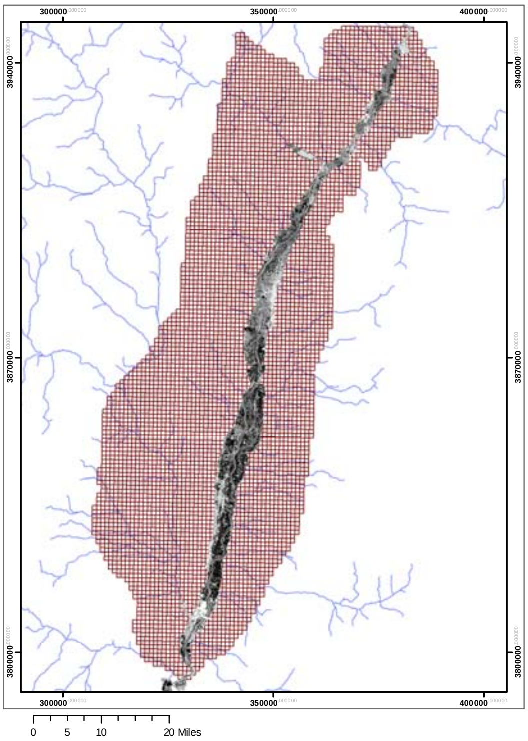

Figure 5. Regional groundwater MODFLOW model with IKONOS derived riparian areas.

4. MODELING FRAMEWORK

The Object User Interface (OUI) is a computer application providing a framework to couple environmental resources models and to manage associated temporal and spatial data. OUI is designed to be easily extensible to incorporate models and data interfaces defined by the user. Additionally, OUI is highly configurable through the use of a user-modifiable, text-based, control file that is written in the eXtensible Markup Language (XML).

OUI is written in Java and XML. This gives modelers and developers a high degree of flexibility in hardware and user interface configuration. OUI components run either as stand alone applications or as an integrated system allowing modelers to assemble components as needed for their models. Also, developers can extend OUI for a specific modeling project. Configuration and extension of OUI is possible without modifying the basic OUI system.

OUI can integrate with other programming languages, most notably C and FORTRAN, on either the system or process level. Software compiled into a computing platform specific executable (referred to as native code) can be called by OUI via a system call. In this way legacy codes can continue to be used with minimal modification. Additionally, OUI can also invoke native code using the Java Native Interface (JNI). In this case, the software compiled into a dynamically loaded library (DLL) can be invoked as needed by OUI during execution.

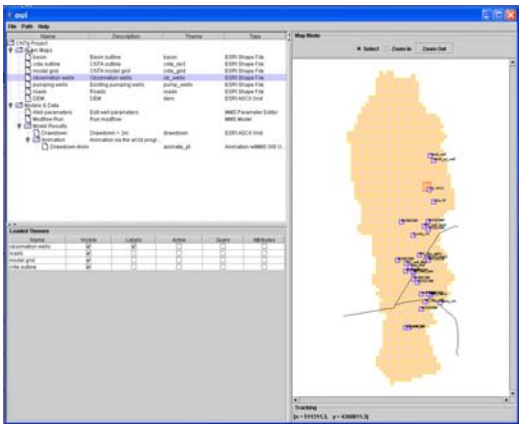

Figure 6. Object User Interface (OUI).

5. PROJECT STATUS AND FUTURE WORK

The incorporation of each of the three models (streamflow generation, river operations, and regional groundwater) into the OUI environment is ongoing. Currently, all three models run independently without dynamic feedback from within the OUI environment (Figure 6). The order of operations is: (1) generate streamflow hydrographs in the headwater basins using MMS-PRMS; (2) using the MMS-PRMS streamflow hydrographs, run the URGWOM river routing and operations model; and (3) using recharge estimates from MMS-PRMS, run the MODFLOW model. The amount of interaction among the models in the future will be directly related to the complexity of the scenarios proposed by the SAHRA economists. At this point, the scenarios are still in the development stage; however, we know that there is a desire to experiment with scenarios that involve alternative groundwater pumping schedules, diversions, crop types, industrial/municipal growth, and climate change. As the details of the scenarios become clear, model integration will move forward and results will be presented and published. Detailed examples of current integrated model capabilities will be presented at the MODSIM conference in December, 2005.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Leavesley, G.H., R.W. Lichty, B.M. Troutman, and L.G. Saindon (1983), Precipitation-Runoff Model System: User's Manual, *U.S. Geological Survey Water Resources Investigation Report* 83-4238.

Leavesley, G.H., P.J. Restrepo, S.L. Markstrom, M. Dixon, and L.G. Stannard (1996), The modular modelling system - MMS: User's Manual, *U.S. Geological Survey Open File Report* 96-151, 142.

Markstrom, S.L., G. McCabe, and O. David (2002), Web-based distribution of geo-scientific models, *Computers & Geosciences*, v. 28, 577-581.

McAda, D.P., and P. Barroll (2002), Simulation of Ground-Water Flow in the Middle Rio Grande Basin Between Cochiti and San Acacia, New Mexico, *U.S. Geological Survey Water-Resouces Investigations Report* 02-4200.