WATER OPERATIONS MODEL DEVELOPMENT TO SIMULATE SURFACE-WATER AND GROUND-WATER INTERACTIONS

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Abstract

The Upper Rio Grande Water Operations Model (URGWOM) simulates flow in the Rio Grande and its major tributary, the Rio Chama, in New Mexico using RiverWare modeling software. Above Cochiti Lake, where the river system is driven by complex reservoir operations with uncomplicated reach losses and gains, the model currently (2005) provides a sufficient representation of the flow system. In the Middle Rio Grande Valley (Middle Valley), from just below Cochiti Lake to the upper end of Elephant Butte Reservoir, complex interactions between surface water and ground water affect flow in the Rio Grande. Flow in the Middle Valley is currently simulated by URGWOM using relations developed with historical data. These relations represent average conditions. Model uncertainty is a result of the variability of the hydrologic system throughout the Middle Valley. Hydrologic simulation of the Middle Valley is being conceptually redesigned from a model based on relations that give an average condition to a model based on simulation of the processes involved in surface-water, ground-water, and evapotranspiration interaction. A direct linkage between RiverWare and MODFLOW is being investigated as well as development of surface-water, ground-water, and evapotranspiration interaction methods in RiverWare.

INTRODUCTION

A major cooperative effort to develop a water operation, accounting, and planning model for the Upper Rio Grande (fig. 1) was started in the fall of 1995 by the Bureau of Reclamation, U.S. Army Corps of Engineers, and U.S. Geological Survey. Prior to 1995, unconnected methodologies were used for water accounting, but no unified methodology was available to help with water-operations decisions. The Upper Rio Grande Water Operations Model (URGWOM) now provides a unified methodology that is used to help make water-operations decisions including releases from upstream reservoirs to meet irrigation demands, maintain specific flows at gaging stations, and adjust releases to meet obligations for the Rio Grande Compact. Currently (2005), URGWOM simulates water operations in the Rio Grande and selected tributaries from the Colorado-New Mexico border to Elephant Butte Reservoir.

Above Cochiti Lake, the river system is controlled by complex reservoir operations with uncomplicated reach losses and gains. URGWOM currently provides an adequate representation of the flow system upstream from Cochiti Lake. The Middle Rio Grande Valley (Middle Valley), from Cochiti Lake to Elephant Butte Reservoir (fig. 1), is a complex hydrologic system with interactions between the Rio Grande, the shallow and deep ground-water system, the complex drain and canal system, and riparian and crop evapotranspiration. As endangered-species issues and other competing uses of Rio Grande water increase, the need to refine the model to better simulate water operations in the Middle Valley has become more important.

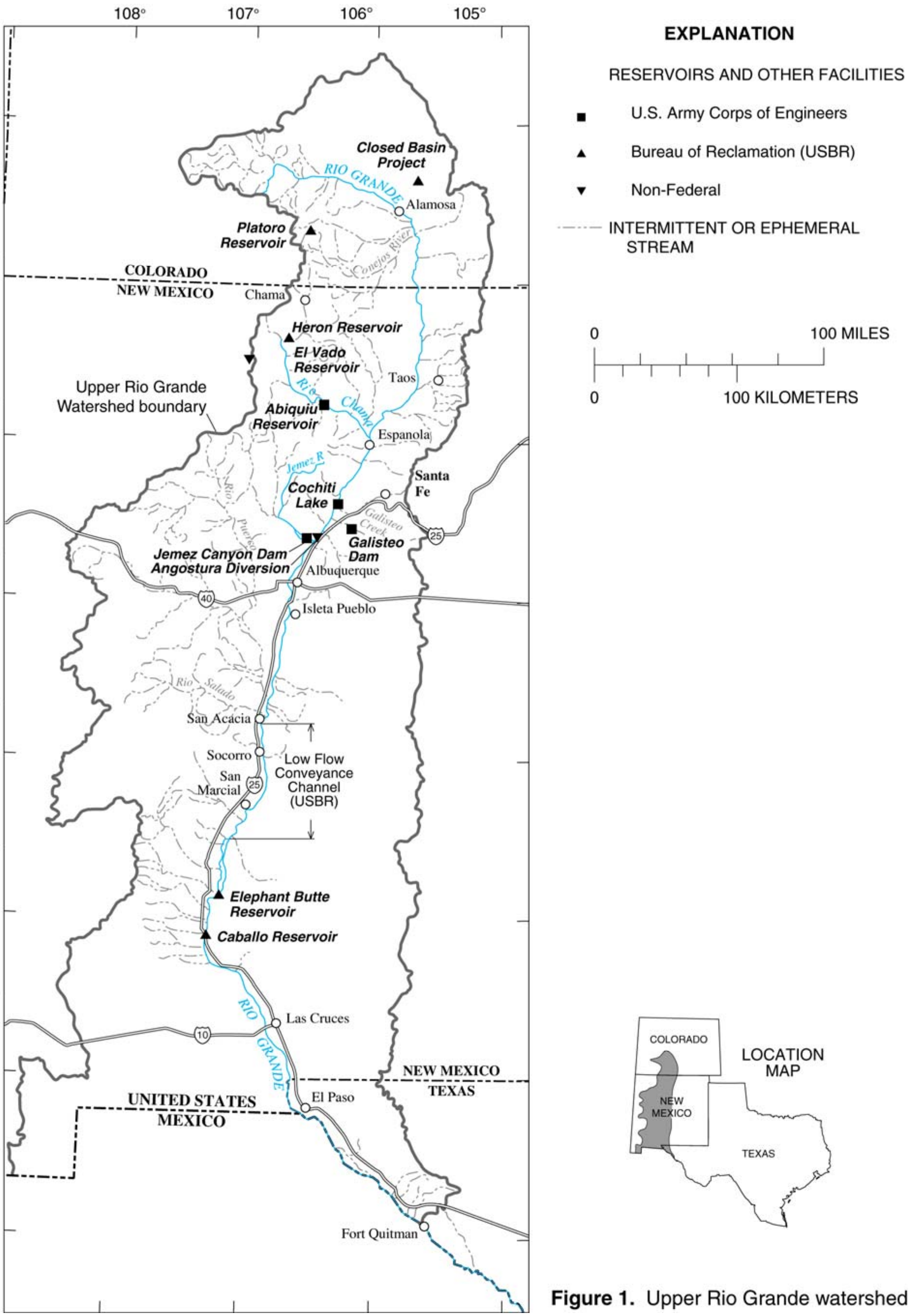

Figure 1. Upper Rio Grande watershed

An effort is underway by the URGWOM Technical Team to refine the simulation of the hydrologic components of the Middle Valley. The current version of URGWOM uses an equation determined by simple regression to calculate the complex losses and gains to the river and therefore simulates long-term average conditions. On a short-term basis, however, there is great variation in the system. Because of the long-term drought that is affecting the Upper Rio Grande Basin, the hydrologic system varies substantially from average conditions. The objective of the Technical Team is to refine the model in the Middle Valley area so that it simulates complex hydrologic processes in the system. With the use of this approach, the observed variability in the system can be simulated more accurately.

HYDROLOGY OF THE MIDDLE VALLEY

Surface-Water System

The Rio Grande in the Middle Valley is in a wide, shallow channel, elevated in relation to the surrounding land surface. The river is confined by levees on both sides of the river and controlled releases from Cochiti Lake. The flow of the river at the most upstream boundary of the Middle Valley averages 1,510 cubic feet per second (Moore and others, 2003). This flow originates from two sources, native Rio Grande water and trans-basin Colorado River water of the San Juan-Chama Project, both of which have to be tracked and accounted for in many parts of the Rio Grande system for regulatory purposes.

There are a few perennial and intermittent tributaries and many ephemeral tributaries to the Rio Grande in the Middle Valley. The Jemez River is the main perennial tributary to the Rio Grande. The other major contributor to the Rio Grande, although not a tributary, is the outfall from the City of Albuquerque sewage-treatment plant. The Rio Puerco, Rio Salado, and Galisteo Creek are major intermittent contributors to the Rio Grande. Numerous arroyos provide ephemeral flow to the Rio Grande throughout the Middle Valley.

Currently four major diversions from the Rio Grande are used for irrigation in the Middle Valley; from north to south, the diversions are Cochiti Dam, Angostura Diversion, Isleta Pueblo, and San Acacia. Water is delivered to canals on both sides of the river by Cochiti Dam. The average total diversion to the two canals for water year 2000 was about 133 cubic feet per second. The average diversion at Angostura Diversion which is just above the confluence of the Jemez River and the Rio Grande, for water year 2000 was 192 cubic feet per second. The diversion at Isleta Pueblo averaged 345 cubic feet per second in water year 2000 and the diversion at San Acacia averaged 149 cubic feet per second in water year 2000. In 2006, the City of Albuquerque will begin diverting about 94,000 acre-feet per year (about 130 cubic feet per second) (*www.cabq.gov/waterresources/sjc.html*) from the river for municipal supply.

Flow from the irrigation diversions is channeled to farms through a complex network of canals and drains in the Middle Valley. A series of riverside drains was installed in the 1930's in response to waterlogging of agricultural land, which became a problem in the early part of the 20th century. During the irrigation season, drains also are used for irrigation conveyance. Most flow in the canal system is ungaged, but more gaging stations are currently (2005) being installed. Some of the diverted irrigation water remains in the canal system and is transferred downstream or returned to the river.

Ground-Water System

The ground-water system in the Middle Valley is composed of a shallow alluvial aquifer within alluvium of Quaternary age (Thorn and others, 1993) and a deep basin-fill aquifer of Tertiary age. For this discussion, the shallow aquifer is characterized by the aquifer's quick response to changes in stage of the Rio Grande and irrigation canals. This response to changes in stage propagates a short distance laterally on either side of the river and is dampened by the riverside drains. The thickness of the quick response zone varies throughout the Middle Valley and is dependent on local vertical and horizontal hydraulic conductivity and distance from the river. The horizontal hydraulic conductivity of the shallow aquifer varies throughout the valley, but generally the conductivity can be as much as 100 feet per day in some areas (Roark, 2001). Due to the large value of horizontal hydraulic conductivity, during the non-irrigation season (November-February), most of the flow in riverside drains is derived from intercepted river leakage.

In the Middle Valley there are about 79,900 acres of irrigated farm land (*http://www.spa.usace.army.mil/urgwom*). Most of the water used for irrigation goes to either evapotranspiration (about 1.6 inches per year) or percolation (about 1 foot per year) to the shallow ground-water system. About 3.6 feet per year of water is transpired by riparian plants that grow in a narrow corridor adjacent to the river, locally called the "bosque".

All of the municipal water-supply wells in the Middle Valley withdraw water from the deeper aquifer. This aquifer can be as thick as 14,000 feet in the center of the valley (Thorn and others, 1993). River-stage fluctuations cause only minor ground-water-level changes in the deep aquifer.

A regional ground-water flow model developed for the Albuquerque Basin, which extends from Cochiti Lake to San Acacia, (Kernodle and others, 1994) simulates stresses to the deep aquifer system using different pumping scenarios. The shortest time step for the regional ground-water-flow model is 6 months. The ground-water-flow model simulates flow in the shallow and deep aquifers and surface-water features to some extent.

METHODS FOR SIMULATING THE HYDROLOGY

Basic Methods in RiverWare

RiverWare[1], the modeling software used for URGWOM, is an object-based water-operations modeling system. More information about RiverWare objects and methods can be found at the CADSWES web site (*cadswes.colorado.edu/riverware)*. A daily time step is used for URGWOM to simulate the detail needed for daily water operations. Many different types of objects are designed for simulating different parts of a river system.

[1] Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

The two objects of concern in RiverWare for this discussion are the reach object, which simulates processes in the river, and the ground-water object, which simulates processes in the quick response zone of the shallow ground-water system. A set of solution methods (methods) for different types of simulation is contained in each object. The user can select the method desired, and enter the data required for the method into URGWOM. Several methods in RiverWare are available to simulate losses or gains between the river and the ground-water system. Most of the methods are based on an equation that describes the relation between one or more independent variables and the loss or gain to the reach object. Two methods use Darcy's equation to determine head-dependent flux into or out of a reach object but do not link the flux to any other objects.

Two other computations of RiverWare are important for determining the required flow released from Cochiti Lake, the accounting computations and the target-flow computations. The accounting computations track the flow of the different types of water, native or trans-basin, through the Middle Valley. The target-flow computations use a function in RiverWare called hypothetical simulation that computes the flow in a reach for a specified number of time steps into the future. This computation is required to estimate how much water must be released from the reservoirs in the system to meet required flows at a given time at the gaging stations at Albuquerque, Isleta Pueblo, San Acacia, and San Marcial. Both computations require continuous reaches for RiverWare throughout the Middle Valley so there are no gaps between objects. These two computations will become increasingly important as the need to track water delivered to many different destinations is required.

Current URGWOM Simulation for Surface-Water/Ground-Water Interaction

The current method used in URGWOM for surface-water/ground-water (SW/GW) interaction is "Seepage and Riparian Consumptive Use Loss." This method determines the amount of leakage from the river for each month using equation 1.

$$\text{Leakage} = n_1 * \log(\text{inflow}) + n_2 * (\text{inflow})^2 + n_3 * \text{inflow} + n_4 * \text{Riparian CU} \quad (1)$$

The independent variables used in used in URGWOM are daily inflow (inflow in eq. 1) and riparian consumptive use (CU). Daily inflow is the flow at the upstream end of each simulation reach. Riparian CU is equal to the daily consumptive use reported for bosque land type by the Bureau of Reclamation's Evapotranspiration (ET) Toolbox (*www.usbr.gov/pmts/rivers/awards*). The coefficients ($n_1 ... n_4$) were determined by regression fit based on leakage, which was derived using Darcy's equation from an analysis of flow between the river and the surrounding drains. The coefficient n_2 was set to zero because that term was not significant. Calculated leakage to the shallow ground-water system represents the average condition for that month over many years and does not account for the variability in daily SW/GW interaction.

Proposed Surface-Water/Ground-Water Interaction Concepts

Two approaches are being investigated for simulation of shallow SW/GW interaction in the Middle Valley. The first approach dynamically links RiverWare to ground-water flow-model software such as MODFLOW; the second approach develops methods and objects in RiverWare to simulate SW/GW interaction.

RiverWare-MODFLOW Linked Approach

Requirements must be met before linking RiverWare to a ground-water-flow model. Calibrated SW/GW interaction ground-water model(s) must exist that separately or together cover the entire area of URGWOM. The only reach of the Rio Grande that SW/GW interaction is simulated fully extends from San Acacia to Elephant Butte Reservoir (Nabil Shafik, Interstate Streams Commission, oral commun., 2004). Other reaches in the Middle Valley have been modeled but only from the river to the riverside drains, because the reaches were constructed to only simulate hydrologic conditions in the riparian area. These riparian-model simulations do not encompass the area needed to fully simulate SW/GW interaction across the valley. For the ground-water flow-model approach to be used, SW/GW interaction ground-water models will have to be constructed or modified to include most of the Middle Valley. The ground-water models will have to link to RiverWare to provide iterative processes for solution of the system at a daily time step. Primary concerns in the dynamic linkage of RiverWare to a ground-water model include the accounting and target-flow computations that are needed for the Middle Valley and the speed of the overall simulation with an iterative link between the two models solving on a daily time step. If the RiverWare reaches are not continuous throughout the Middle Valley, the accounting and target-flow computations cannot be accomplished. Because RiverWare and the ground-water flow model will have to iteratively solve for each reach and move data between the two models, the computation time of the linked model will likely steeply increase compared to RiverWare alone.

RiverWare-Based Approach

Currently, RiverWare does not include robust SW/GW interaction methods. The simulation of complex SW/GW interaction will require development of methods for the reach and ground-water object. This type of physically based simulation will be generalized by areal detail compared with simulation using a ground-water model, such as MODFLOW. A generalized simulation fits sufficiently with the current amount of data density and understanding of SW/GW interaction in the Middle Valley. Because it is planned that the refined Middle Valley simulation be based on physical processes, the methods that will be developed must account for the physical processes involved with SW/GW interaction. Most of the new methods will be centered on head-dependent flux between the reach and ground-water objects.

For the refined Middle Valley model, the current reaches will be divided into shorter reaches to minimize the error associated with changes in river slope between the upstream and downstream ends of a reach. For each reach in the model, there will be a ground-water object to simulate the shallow ground-water system beneath the river. Ground-water objects can be added to either side of the ground-water object beneath the river to simulate the local hydrologic conditions at each reach. The ground-water objects in a cross section will be linked together hydraulically using Darcy's equation, and will be linked to the ground-water objects in cross sections upstream and downstream. Because the objects are linked, accounting and target-flow computations can be done. Flow into or out of the deeper ground-water system will be simulated by an input into the ground-water objects to determine flux to or from the deep ground-water system. Depending on the type of computational solution for the SW/GW interaction objects, computational time of the simulation might be an issue.

The new reach-object method will use the current head-dependent flux method to determine streamflow loss or gain but with some changes. The reach object will have a streambed hydraulic conductivity, thickness, average bottom elevation, input for the length, and width of each reach. As long as the head in the shallow aquifer is higher than the bottom of the reach object streambed elevation, then head-dependent flux will be calculated between the reach and the ground-water object using Darcy's equation. If the head in the shallow aquifer is lower than the bottom of the reach object streambed elevation, then flux to the shallow ground-water system will be a constant flux dependent on the hydraulic conductivity and thickness of the bed. This simulation requires links between the reach and the ground-water objects to pass information such as head and flux between the two objects.

The river head in the reach objects may be constantly changing depending on flow in the river. The river head for the SW/GW interactions will be the average head for the reach determined by the current method for head-dependent flux.

The greatest change to the current RiverWare methods will be to the current ground-water object. The ground-water system will be simulated using different methods. The ground-water object will be used to simulate the shallow aquifer, in which rapid changes in head occur in response to changes in river stage. The ground-water object will have functionality developed to simulate an aquifer using the hydrologic properties of storage, horizontal and vertical hydraulic conductivity, and computation of an unconfined ground-water surface.

The stream reaches will lose or gain water through the object in a way that simulates natural processes. Most losses or gains to the river occur through the shallow ground-water system, so the losses to riparian evapotranspiration and to the deep ground-water system, and the losses or gains from deep percolation from crop areas and canal leakage, will be simulated as flux out of or into the ground-water objects.

In the deep ground-water system, from which most municipal water is pumped, effects of fluctuations in river stage are dampened such that river stage can be simulated as a constant head. The deep ground-water system can then be simulated using the regional ground-water-flow model (Kernodle and others, 1994) as a change in head over the period of time to be simulated and entering the response as a time series of heads or seepage data in the ground-water object.

SUMMARY

The Middle Valley section of the URGWOM model, from Cochiti Lake to Elephant Butte Reservoir, is a complex hydrologic system governed by close interaction among the Rio Grande, the ground-water system, a complex drain and canal system, and riparian and crop evapotranspiration. Current simulation of SW/GW interaction in the Middle Valley uses an equation that does not account for observed short-term variability but estimates the average condition. Two solutions have been investigated to improve simulation of SW/GW interaction in Middle Valley: development of a ground-water model dynamically linked to RiverWare and development of RiverWare methods to simulate SW/GW interaction. Both methods have strengths and weaknesses.

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