***J. Phillip King** is an associate professor and associate department head in the Civil Engineering Department at New Mexico State University, where he has been since 1990. He specializes in water resources engineering, and his research has included irrigation, hydrology, and water quality studies of the Rio Grande. He has worked with Elephant Butte Irrigation District since 1991 in the development of flow monitoring systems and organizational infrastructure to allow the District to manage its water supply more effectively, and he provides technical support for dispute resolution on area water issues. Phil has worked with irrigators, municipalities, Native American tribes, and World Wildlife Fund to develop new approaches to water management. He served as a Peace Corps volunteer in Malawi. Phil has Ph.D. and M.S. degrees in agricultural engineering from Colorado State, a B.S. in civil engineering from Berkeley, and an M.B.A. from NMSU.*

GROUNDWATER AND SURFACE WATER MODELING FOR WATER PLANNING

Phil King
New Mexico State University
Civil and Geological Engineering
Box 30001, Dept. 3CE, Las Cruces, NM 88003

Nabil Shafike
New Mexico Interstate Stream Commission
121 Tijeras NE, Suite 2000, Albuquerque, NM 87102

Introduction

Water resources managers and planners are faced with the task of identifying optimal or near-optimal solutions in highly complex systems. One of the most important classes of management tools is models, which provide an analytical framework for evaluating likely outcomes of various natural and management scenarios.

While the hydrologic systems that models represent are infinitely complex, modelers use fundamental hydraulic and hydrologic principles with acceptable simplifying assumptions to create a mathematical formulation to evaluate the behavior of the hydrologic system under various system designs and operating policies. Depending on the complexity of the mathematical model, it may be solved analytically or numerically. The rise of computers has made sophisticated numerical solutions widely applied. Because of the different hydrologic, temporal, and spatial characteristics of surface water and groundwater systems, models tended to focus exclusively on surface or subsurface hydrology. As water managers have found that the problems of surface water and groundwater are inexorably linked, modelers have developed closely coupled models to better represent the interaction between the two hydrologic regimes.

This paper describes the evolution and application of three modeling case studies that illustrate the utility of computer-based models for water planning and management. The first is primarily a groundwater modeling effort in the Middle Rio Grande, a MODFLOW model of the aquifer system underlying the Albuquerque area. The second is primarily a surface water model, a RiverWare model of the storage and delivery operations on the Rio Grande from its headwaters in Colorado to Caballo Dam. The third is an externally linked surface water/groundwater model of the Pecos River in New Mexico. Finally, a model under development in the San Acacia reach of the Rio Grande presents an example of a more closely linked representation of surface water/groundwater interaction.

Need for Hydrologic Models

While this paper focuses on hydrologic modeling for planning, there are several other uses for water models, for example in engineering design, in which the engineer simulates individual flood events to get design flows, so that the system to be designed will have adequate capacity. Our focus is on larger scale models for planning.

Models help us to take diffused, scattered, and very complicated data, and use that in a modeling format to develop a quantitative understanding of that data. In fact, we would even go beyond quantitative, to an executable understanding of that data. Secondly it provides a scientific and objective basis for water management and for the administration of water resources. For example, the State Engineer needs tools that he can point to and say, these are the methods by which we will evaluate whether or not you are negatively impacting other water rights holders. They will be based upon the best scientific understanding and data, unbiased, and objective.

Models can be used to help us understand what has happened under past management regimes and hopefully by understanding the strengths and weaknesses of past management regimes, we can plan better for the future and to evaluate or potentially even optimize our management options for water planning and management.

In developing a model for water use planning, it is important to be sure that (1) the model will answer the relevant management questions and (2) sufficient data and understanding of the system are available to create a representative model. If you are asking very simple questions, you will get by with a very simple model. Similarly, if you really don't have much relevant data, it doesn't help to put it in a big, complex model. However, if you are asking very complex, very important questions, which we are all doing in this planning process, you need very sophisticated and very data-rich models to meaningfully answer those questions.

Types of Models

In describing types of models, we stress that most functional models incorporate elements of each type we discuss here. However, it is useful to examine the basic types as separate entities for clarity.

Statistical models rely on historic behavior of hydrologic systems, and characterize them statistically by parameterizing their statistical distribution or by some sort of time-series model. For example, a 100-year return period, 24-hour duration rainfall in Las Cruces is 3.8 inches. This means that, based on statistical analysis of rainfall records for the area, in a given year, there is a 1/100 chance of getting more than 3.8 inches of precipitation in a 24-hour period. Note that the hydrologic processes by which precipitation occurs are entirely left out of the model.

Hydraulic and hydrologic models focus on the physical processes that statistical models neglect. The simplest of such models are the analytical models. An analytical model is a model where we formulate our understanding of the hydraulics of water movement and develop mathematical models that we solve explicitly to describe the behavior of a hydrologic system. An example of this would be the Theis Method[1] for examining the effects of pumping groundwater from an aquifer. The Theis formula expresses drawdown in an aquifer as a function of distance from the well and time of pumping. The formula is:

$$h_o - h(r,t) = \frac{Q}{4\pi T}\int_u^{\infty}\frac{e^{-u}du}{u}$$

where h_o is the initial piezometric level in the aquifer (before pumping), h(r,t) is the piezometric level in the aquifer at time t since pumping began and distance r from the pumping well, Q is the rate of pumping, and T is the transmissivity. It is simple and quite commonly used. However, in order to get the model simple enough so that we can solve for it mathematically, we have to make several simplifying assumptions. Theis assumes that the aquifer has infinite lateral extents, that it is homogenous, that is, the properties of the aquifer don't vary around the aquifer, and so on. These are very major simplifying assumptions, but often we are asking fairly simple questions, so we can live with them. For example, if you have a small well and a big aquifer, it is probably acceptable to make these assumptions.

Numerical Models

The numerical models are much more flexible regarding the necessary simplifying assumptions. This approach takes advantage of the rise of computing resources and the growing body of data available to us to build much more sophisticated models that are capable of answering much more sophisticated questions.

To illustrate this modeling approach, we look at four case studies: the Middle Rio Grande groundwater model, focusing very much on groundwater hydrology. The Upper Rio Grande Water Operations Model (URGWOM) is a surface water model. A model of the Pecos River is an example of a semi-combined surface water/groundwater model. Finally, a more recent model of the San Acacia reach of the Rio Grande represents the interaction between surface water and groundwater in more detail.

Middle Rio Grande Groundwater Model

We stress that the development of any model is an evolutionary process, and while at any stage of this evolution there is a product, the evolution never ends. The current generation of numerical modeling of the Middle Rio Grande groundwater system began with a MODFLOW (a U.S. Geologic Survey modeling package) model by Kernodle,[2] and has been updated. Analytical models were used for planning purposes in the area before Kernodle. The model developed in stages, the objective being to look at the effect of groundwater pumping on the river, on potential Rio Grande Compact implications, and so on. If you wait until you have full data on a hydrologic system before you develop a model, you will never develop a model, hence the evolutionary approach. This model, shown in Figure 1, goes from Cochiti to San Acacia. It represents an infinitely complicated hydrogeologic system that is discretized, divided up into kilometer squares, each one of which has the average hydrologic properties of that square kilometer. Unlike Theis, the representation in this model has lateral limits and is heterogeneous, and its representation is much more realistic than that of Theis.

The plan view in Figure 1 represents the lateral variability in the groundwater system. Vertical variability is represented by layers, shown in Figure 2.

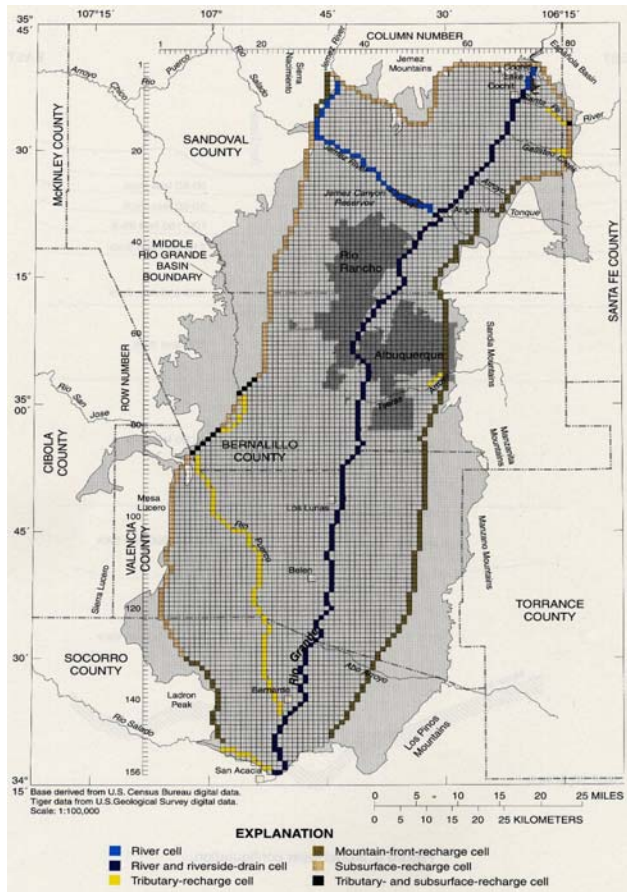

Figure 1. Plan view of Middle Rio Grande groundwater model.

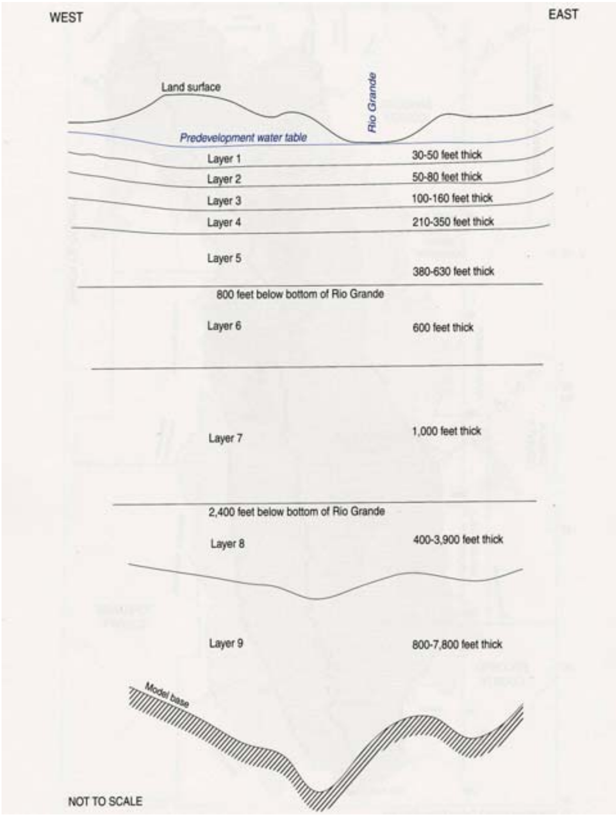

Figure 2. Cross section of Middle Rio Grande

This is strictly a groundwater model; surface water is represented in it but it is almost an artifact. The URGWOM, on the other hand is primarily a surface water model and conceptually it is completely different.

A number of agencies have been involved in the development of URGWOM. It is developed using RiverWare Software, which is a river modeling package, sort of the surface water equivalent of MODFLOW. It currently is being developed for the Rio Grande from the Colorado state line to El Paso, Texas, and again its development is ongoing and probably will always be ongoing. It allows river managers to simulate the operational effects of reservoir operations, floods, irrigation, municipalities and industrial uses, the use by Native American tribes and channel losses. It also incorporates river accounting systems such as the Rio Grande Compact. A schematic of the model from one of its operating screens is shown in Figure 3.

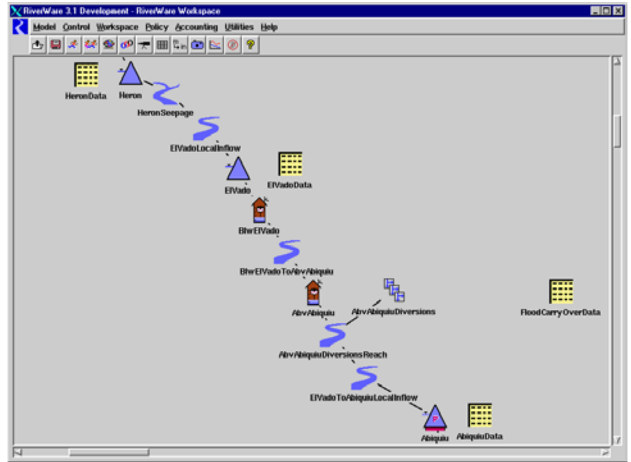

Figure 3. URGWOM schematic screen.

This is a fundamentally different conceptualization of the system that the Middle Rio Grande groundwater model used. Rather than a three-dimensional grid and layer system, this is very much a linear structured model with nodes along the river that represent measurement and control points. They are connected with links that represent the characteristics of the river channel and its effect on flow. One of the problems with trying to isolate either groundwater, and modeling in the absence of surface water, or modeling surface water in the absence of modeling groundwater models, is that the two are so highly interactive that separation is often an unacceptable simplification.

Combining surface water and groundwater models to better represent reality is a difficult undertaking. First of all, they tend to operate on very different temporal scales. Not only do we discretize things spatially, the MODFLOW with the layers and grid, and the RiverWare with the nodes and links, we discretize things temporally. Each of these models has an operating time-step. The operating time-steps in a typical groundwater model and a typical surface model are extremely different. Groundwater models tend to run on time-steps something along the order of months to a year; things tend to move more slowly through the groundwater system. With a surface water system, if you were releasing water from Cochiti and you wish to route that through the Albuquerque reach, a time step of a few minutes to a few hours would be appropriate. It may take multiple days for the flow to make it through the section, but you do have to track it in much shorter time-steps.

An example of an effort to reconcile the different conceptual models and represent the interaction between surface water and groundwater was developed on the Pecos River, one of our more controversial rivers, by Interstate Stream Commission and State Engineer staff working along with Reclamation, Intera, and Hydrosphere. They developed a decision support system that links surface water and groundwater models. Basically it depends on a groundwater model for the Roswell-Artesian Basin and another one for the Carlsbad area, and through it runs a Riverware model. A schematic of the model is shown in Figure 4, and a flow chart of its computational logic is in Figure 5.

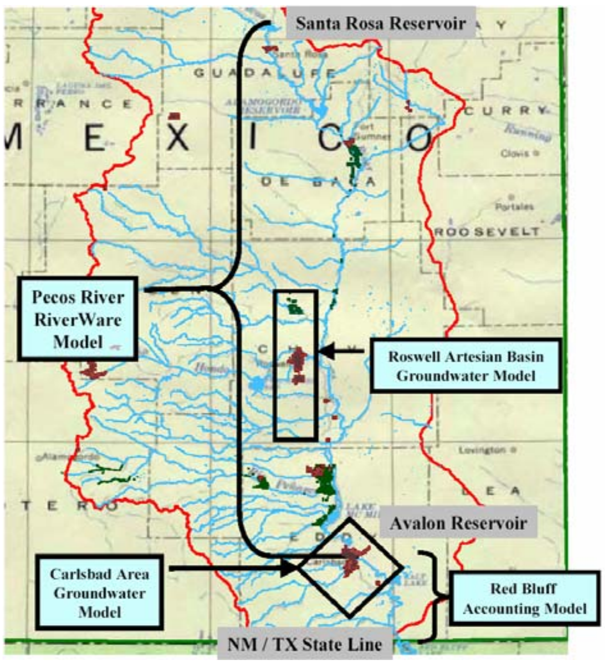

Figure 4. Schematic of Pecos River decision support system, combining groundwater models with a surface water model.

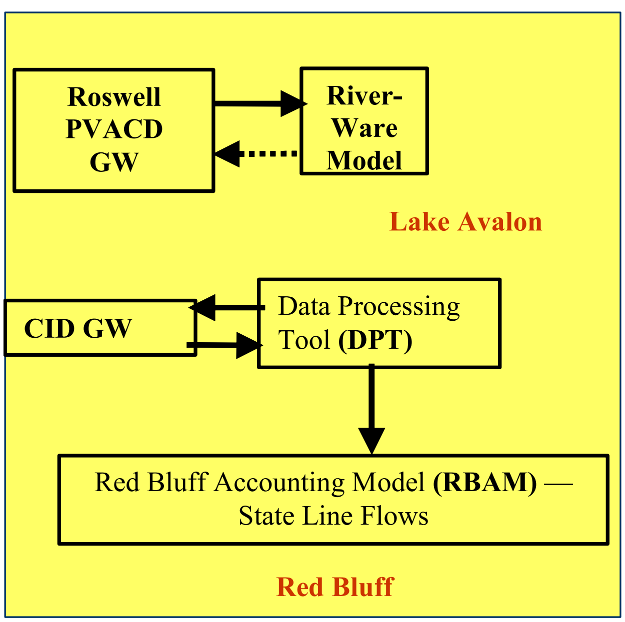

Figure 5. Flow chart of Pecos River decision support system.

The Pecos River decision support system relies on external linkages between essentially stand-alone surface water and groundwater models. A more integrated approach is being developed on the San Acacia reach of the Rio Grande by the Interstate Stream Commission. The objective is to simulate the effect of operation of the Low-Flow Conveyance Channel on seepage losses from the river. Note in Figure 6 that the model, developed using MODBRANCH (A USGS package for modeling stream-aquifer interaction), the representation of the groundwater system is much like that of MODFLOW, and the representation of the river is much like that of RiverWare.

The logic of the MODBRANCH model of the San Acacia reach is shown in the flow chart of Figure 7. Rather than stand-alone models that are reconciled externally, MODBRANCH compares results of the two systems during each time step. This is computationally intensive, one of the reasons for the smaller geographic extent of this model.

As modeling tools improve and computer speed increases, we anticipate seeing more models of this general type that explicitly recognize the connection between surface water and groundwater systems, and model them in an integrated fashion, much as they exist in nature.

ENDNOTES

[1] Theis, C. V., 1935. *The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage*. Transactions of the American Geophysical Union, 2, pp. 519-524.

[2] Kernodle, J.M., D.P. Mcada and C.R. Thorn, 1995. *Simulation of Ground-Water Flow in the Albuquerque Basin, Central New Mexico, 1901-1994, with Projections to 2020*. Water-Resources Investigations Report; US Geological Survey, Albuquerque, NM.

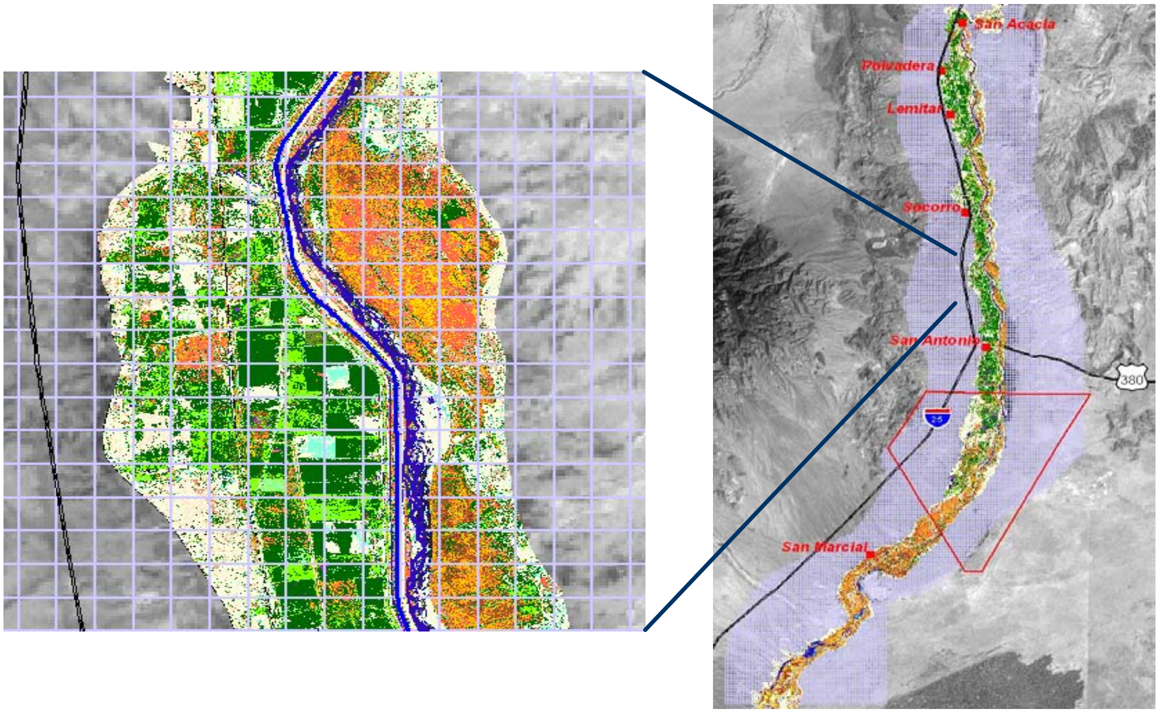

Figure 6. San Acacia reach MODBRANCH model, intended to simulate the effect of Low Flow Conveyance Channel operations on river seepage.

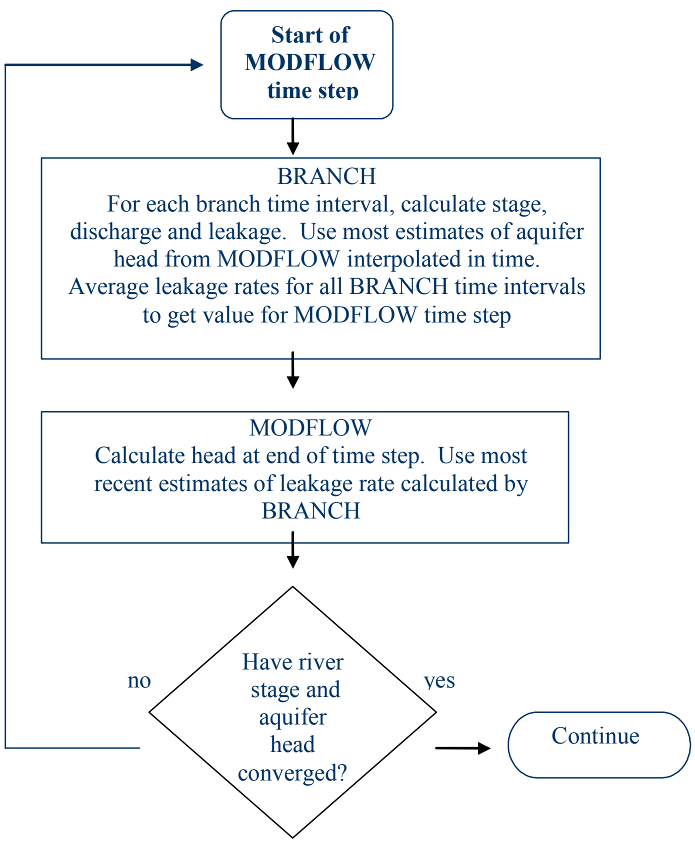

Figure 7. Overview flowchart of San Acacia reach MODBRANCH model.