Incorporating groundwater-surface water interactions into river management operations by linking an object-oriented decision support model (RiverWare) with MODFLOW

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ABSTRACT

Accurate representation of groundwater-surface water interactions is critical to modeling low river flow periods in riparian environments in the semi-arid southwestern United States. A link between the object-oriented decision support model RiverWare and MODFLOW was developed to incorporate critical features such as riparian evapotranspiration, localized variations in seepage rates, irrigation return flows and rule-based water allocations to users and/or environmental flows. Specifically, the link allows variables associated with MODFLOW's RIV, STR, SFR, and GHB packages to be exchanged with RiverWare's Reach, Groundwater Storage, Water User, and Aggregate Diversion Site objects and vice versa. Exchange of data is handled using RiverWare's computational subbasin structure. Since the MODFLOW grid is likely to be at a finer resolution than RiverWare objects, the user is able to specify multiple MODFLOW cells as interacting with a single RiverWare object. Accordingly, spatial interpolation and summation between some exchanged variables is necessary. An interactive time stepping approach is used to link the two models, in which both models run in parallel exchanging data after each time-step. The performance of the linked RiverWare-MODFLOW model is illustrated through applications on the Rio Grande in the vicinity of Albuquerque, New Mexico, where over-appropriation of human water use in the region adversely impacts the habitat of the endangered Rio Grande silvery minnow.

INTRODUCTION

Surface-groundwater interaction is a critical component of the hydrology of riparian zones. Accurate representation of water balance in these systems is complicated by several factors, including riparian evapotranspiration; artificial structures, such as diversions, canals and drains; and complex patterns of water consumption related to water rights and allocations. Especially during low flow periods where it is necessary to account for small volumes of water accurately, there is a need for sophisticated high-resolution models of surface-groundwater interaction that accurately capture both physical processes and human aspects of water flow and transfers through a riparian corridor. Several packages exist within MODFLOW to represent surface-water features and their interaction with groundwater. Previous efforts have coupled MODFLOW with various surface-water flow models (Jobson and Harbaugh, 1999; Swain and Wexler, 1996; and Hydrogeologic, 1996). However, the operational complexities that control flows and diversions within the main river channel and associated network of drains and canals is typically not represented in the above models, which focus primarily on physical process interactions. This work was motivated by a need to integrate the operational complexities of river systems with physical process models, to produce an improved framework for modeling surface-groundwater interactions, in the context of river management during low-flow periods. The Middle Rio Grande Basin in New Mexico exemplifies some of these requirements, and serves as a case study in the work reported here.

RiverWare (Zagona et al., 2001) is an object-oriented interactive physical and operational process model for river basins, in which several alternatives are allowed for individual physical process representations and operational rules. Objects within RiverWare represent natural and human components of a river system, such as river reaches, reservoirs (storage and hydropwer), diversions, water users, and shallow groundwater units. RiverWare is currently used for planning operations in several river basins such as Middle Rio Grande, San Juan, and Colorado River. Current approaches for incorporating surface water-groundwater interactions in RiverWare include empirical regression-based equations for seepage losses based on historical data and the Groundwater objects in RiverWare, which typically represent large areas in a lumped sense. In this work, we describe the development of a link between RiverWare and

MODFLOW to enable high-resolution representation of surface water-groundwater interactions within a riparian corridor.

OVERVIEW OF RIVERWARE-MODFLOW LINK

In this section, we describe the general features of the link between RiverWare and MODFLOW. The link involves explicit coupling between RiverWare and MODFLOW, wherein the models exchange data at the end of each time step, and used MODFLOW 2000 version 1.15, enhanced to incorporate one non-standard MODFLOW package [RIP-ET], (Maddock and Baird, 2003) for modeling riparian evapotranspiration. A new MODFLOW Fortran library was created within MODFLOW's MAIN procedure that allows RiverWare to: start a MODFLOW computation, advance it by one time-step, input data from RIverWare to MODFLOW, read output from MODFLOW and transfer to appropriate slots in RiverWare and end a MODFLOW computation. At this time, sensitivity analysis and parameter estimation are not supported in this link. The link involves the MODFLOW packages: river (RIV), streamflow-routing (STR, SFR) and general-head boundary (GHB); and the RiverWare objects: Reach, Water User, Aggregate Diversion Site and GroundWater Storage. The RiverWare computational subbaasin structure was used for communication between the RiverWare objects and MODFLOW.

A prototype RiverWare-MODFLOW interaction is depicted in Figure 1 (a-plan and b-cross section views). A three-dimensional MODFLOW grid is used to represent the groundwater system within MODFLOW, and several surface water features are superimposed on it. The riparian groundwater system is bounded externally by GHB cells that facilitate communication with a deeper regional aquifer. The regional aquifer heads may be defined based on previously obtained long-term simulation results from a regional aquifer model. RiverWare GroundWater Storage objects are used to define the shallow groundwater heads adjacent to the top-most layer of the MODFLOW model, and also interact with the regional aquifer heads. The main river reach is defined using RIV cells in MODFLOW. Riverside drains and auxiliary surface water features are represented using the STR-SFR package. Inflows to STR-SFR reaches in MODFLOW are represented based on transfers from RiverWare objects, such as diversions and return flows. Outflows from MODFLOW STR-SFR reaches may be transferred to the Reach object in RiverWare as gains or alternately a diversion from the RiverWare Reach object may be transferred to STR-SFR reaches. It should be noted that there are some disparities in the spatial resolution between the high resolution of the MODFLOW grid and the lumped nature of the RiverWare objects, which necessitates the intermediate steps of interpolation (RiverWare object from MODFLOW grid) and summation (MODFLOW grid to RiverWare object) during data transfer. This is facilitated by developing a well-defined mapping between individual RiverWare objects and associated MODFLOW grid cells. For instance, seepage gains-losses from an individual Reach object are computed by summing the seepage values computed for each MODFLOW RIV cell associated with a Reach object, which are in turn based on interpolated river stages derived from upstream and downstream river stage, tracked by each RiverWare Reach object. User-specified weighting coefficients for interpolation allow for either incorporation of information from externally obtained detailed river hydraulics computations, or simple algebraic interpolation. Current implementation of the linked model requires an identical time-step for both RiverWare and MODFLOW. A daily time-step is currently used, which is consistent with the time-step used in operational planning in the Middle Rio Grande basin case study, which motivated this work. Future versions of the linked model may allow for different time-steps and associated temporal interpolation/integration. In the current implementation, it is possible to model a relatively large geographical region, represented within a single RiverWare model that interacts with multiple MODFLOW models.

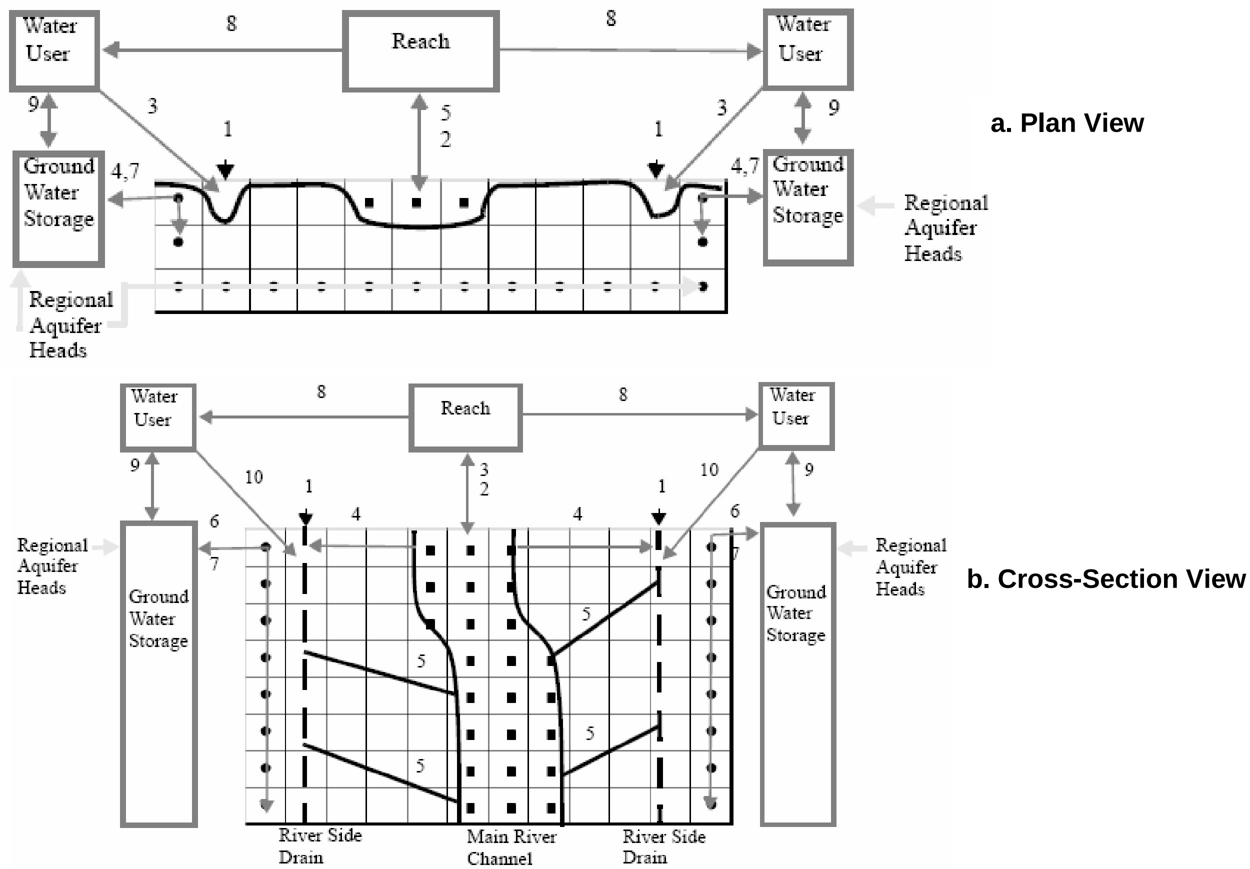

Figure 1. Plan and Cross Section Views of the RiverWare-MODFLOW Interaction. A river corridor is shown which contain a main river channel (bold black lines) and two riverside drains, one on either side of the river (dashed lines). The MODFLOW grid is shown with RIV cells denoted with square markers, GHB cells denoted with circular markers, and the STR or SFR reaches denoted as dashed black lines to the right and left of the main river channel. RiverWare objects are designated as gray boxes. Each data transfer between the two programs is numbered, denoted with an arrow showing direction of data movement. Several additional data exchanges which are likely be used in a RiverWare-MODFLOW Interaction model are also shown.

Data Exchanges:

(1) inflow into riverside drain [in MODFLOW only];
(2) river stage [to MODFLOW]
(3) gain-loss between river and aquifer [to RiverWare];
(4) diversion from river to riverside drain [to MODFLOW];
(5) local inflow-return flow from riverside drain to river [to RiverWare];
(6) GroundWater Storage object head [to MODFLOW];
(7) lateral flux between MODFLOW lateral boundary cell and GroundWater Storage object head [to RiverWare];
(8) diversion from RiverWare Reach object to WaterUser object or AggDiversionSite object [in RiverWare only];
(9) GroundWater Storage object return flow [in RiverWare only];
(10) surface water return flow [to MODFLOW];
Regional aquifer heads are input into RiverWare and MODFLOW by the user

CASE-STUDY: MIDDLE RIO-GRANDE BASIN

The middle Rio Grande basin spans an area of about 3,060 square miles in New Mexico, including the city of Albuquerque. Surface-groundwater interaction in the basin is complicated by the role of riparian evapotranspiration; riverside drains and the extensive network of unlined canals and drains that transfer water back and forth between the river and water users. Current river management efforts employ the Upper Rio Grande Water Operations Model [URGWOM] (USACE, 2007), based on RiverWare, which incorporates a detailed definition of various surface-water features in the basin. Existing MODFLOW models for the basin include the Middle Rio Grande Regional Groundwater Model (McAda and Barroll, 2002) and a set of riparian-zone groundwater models (S.S. Papadopulos and Associates [SSPA], Inc. and New Mexico Interstate Stream [NMISC], 2007; and SSPA and NMISC, 2005). The riparian groundwater models incorporate boundary condition based on simulation results from the regional models, and are useful for representing short-term (daily-weekly) surface-groundwater interactions within the riparian corridor. In this case study, we linked a modified version of the riverware model URGWOM, with two MODFLOW models: (i) the Cochiti model (from Cochiti reservior to Angostura diversion dam) and (ii) the Upper Albuquerque model (from Angostura to Central avenue in Albuquerque). The shallow groundwater system outside the riparian zone is represented using Groundwater objects in RiverWare, and accounts for irrigation/recharge and interaction with the regional aquifer below. Several scenarios in the Middle Rio Grande basin were analysed by Valerio (Valerio, 2008) to evaluate the RiverWare-MODFLOW model. Here, we present results from the historic comparison scenario.

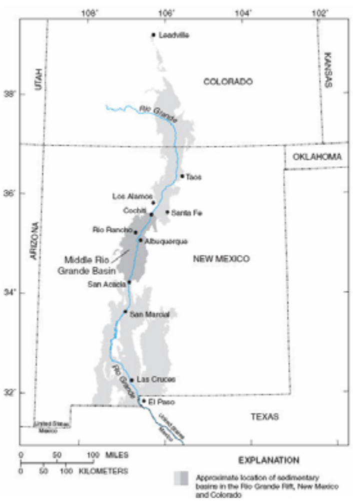

Figure 2. Location of Middle Rio Grande Basin

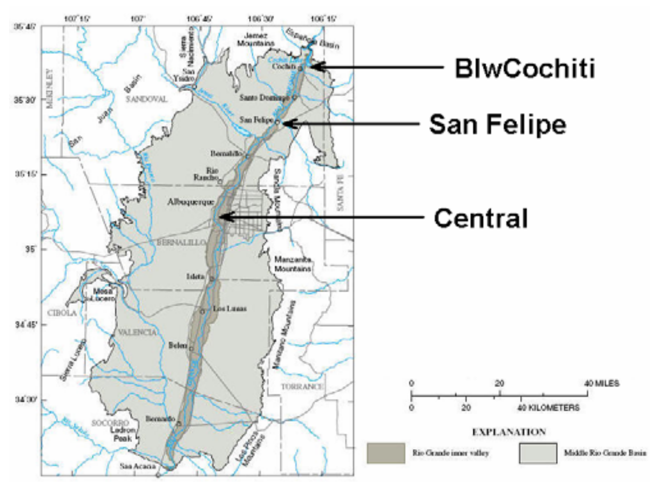

Figure 3. Approximate Location of Flow Gages Along Rio Grande in Middle Rio Grande Basin

This scenario compares modeled data to the historic record at three gages along the Rio Grande in the Middle Rio Grande region (Figure 2 and 3) for the nominally low flow years of 1976-1977. Figures 2 and 3 were modified from McAda and Barroll, 2002 and Bartolino and Cole, 2002, respectively. Figure 4 displays the historic flow data against the RiverWare-MODFLOW Linked model data. Flows produced at the Below Cochiti and San Felipe gages match historic flows very well. While modeled flows at the Central gage show slight differences from the historic record (Figure 4c), the linked model tends to over-estimate flow at this gage. Following are several explanations offered for the observed differences. 1) The differences might be due to the onset of evapotranspiration. Evapotranspiration primarily occurs during the summer and fall months and is not active in the model during the winter. Since the largest differences are observed during summer months they could be due to incorrect evapotranspiration estimates. 2) The differences might be due to incorrect estimates of return canal flow in the model. No gages are present to measure canal return flows in the lower region of the model and thus the model calculated return flows have been estimated and may be a source of error in the model. 3) Lastly, the historic gage data may incorrect. Most of the time the modeled data matches well with the historic flow. However, the modeled flow diverges from historic data just after spiked increases in the flow. Thus it is possible that the gage data during low flow periods may be unreliable due to factors such as a shift in sediment in the channel from flow spikes that can alter the rating curves.

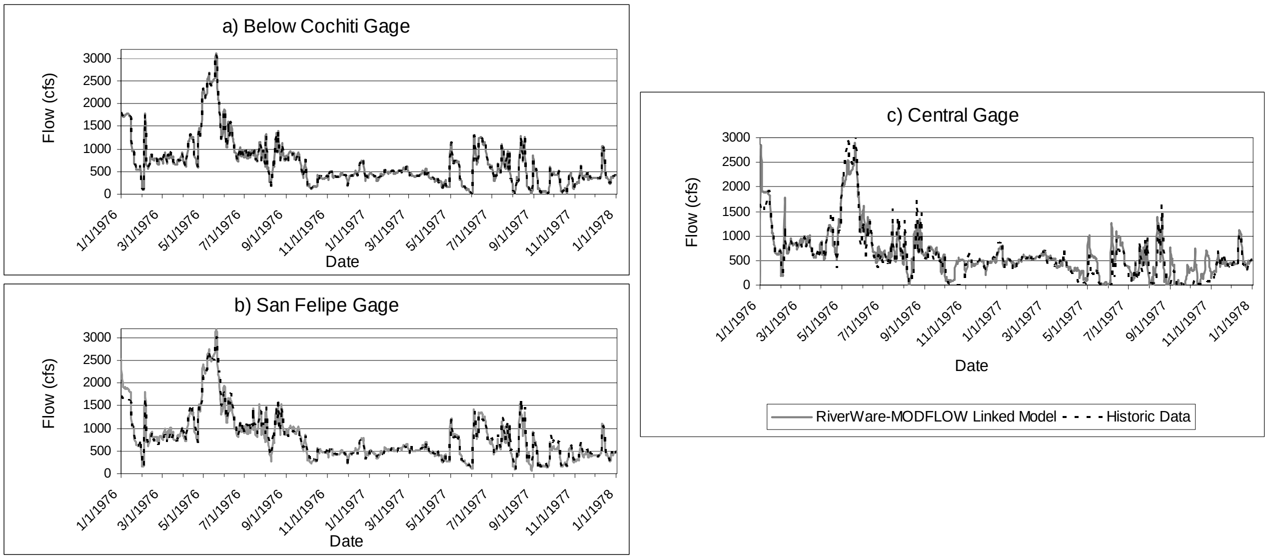

Figure 4. RiverWare-MODFLOW Linked Model Data as Compared to Historic Flow Data for 3 Gages on the Rio Grande (Below Cochiti, San Felipe and Central). Data is shown for 1976 and 1977.

Although, Middle Rio Grande region model needs some refinement to improve agreement with observed flows, overall the linked model produces reasonable estimates of flow in the region. This case study shows that the linked RiverWare-MODFLOW model is a promising approach for managing river sections where dynamic groundwater-surface water interactions influence streamflow. Valerio (2008) presented case studies that illustrate the promise of the linked model for river management during low flows.

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