MODELING GROUNDWATER-SURFACE WATER INTERACTIONS IN AN OPERATIONAL SETTING BY LINKING RIVERWARE WITH MODFLOW

by

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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. This thesis presents a modeling tool with significant potential for improved operational decision-making in river reaches influenced by surface-groundwater interactions.

A link between the object-oriented decision support model RiverWare and the United States Geological Survey (USGS) quasi three-dimensional finite difference groundwater flow model MODFLOW was developed. 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. This linked framework incorporates several features critical to modeling groundwater-surface interactions in riparian zones, including riparian evapotranspiration, localized variations in seepage rates, irrigation return flows and rule-based water allocations to users and/or environmental flows.

The performance of the linked RiverWare-MODFLOW model is illustrated through applications on the Rio Grande near Albuquerque, New Mexico, where over-appropriation of human water use adversely impacts the habitat of the endangered Rio Grande silvery minnow. Improved management practices during low river flow conditions could prevent channel desiccation and habitat destruction. The linked model simulations were evaluated against historic data and two current models for the region. Historic river flows were adequately reproduced by the linked model. Additionally, an investigation of the linked model's sensitivity to low river flow conditions was performed and compared against the two existing regional models. It was found that the gain/loss between the river and aquifer estimated by the linked model was not overly sensitive to changes in river flow. In fact, the model produced similar downstream flows as one of the current models, while displaying less river/aquifer gain/loss sensitivity to the change in river flow conditions. However, when compared against the other current model of the region large discrepancies were apparent in the produced downstream flows. Further analysis revealed that some of these discrepancies may be attributed to model configuration differences. Overall, the RiverWare-MODFLOW linked model offers an improved tool for management of river operations accounting for the relatively rapid groundwater-surface water interactions in riparian zones.

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CHAPTER 1 - INTRODUCTION

Interaction between surface water and groundwater is an integral process in watersheds, governed by climate, geology, surface topology, and ecological factors. Freeze and Cherry (1979) state a “watershed should be envisaged as a combination of both the surface drainage area and the parcel of subsurface solid and geologic formations that underlie it”. However, hydrologic components, such as surface water and groundwater, have historically been treated as separate units and modeled accordingly. In the 1960’s the first groundwater surface water interaction studies focused on the interaction between lakes and groundwater with particular emphasis on effects related to acid rain and eutrophication (Sophocleous, 2002). By 1970, groundwater pumping in several regions was found to influence in-stream flows and a number of studies for conjunctive management of the two resources were conducted (Barlow and Granato, 2007; and Barlow et al., 2003). More recently, the interaction between surface water and groundwater along river corridors has received increased interest due to ecological and climatic concerns (Sophocleous, 2002; S.S. Papadopulos and Associates and New Mexico Interstate Stream Commission [NMISC], 2005; Barlow and Granato, 2007).

Many components make up the hydrologic system of a region; accordingly multiple physical processes must be considered in order to quantify groundwater surface water interaction along a river corridor such as: overland and in-channel surface flow; groundwater flow; hyporheic exchange; surface water evaporation; and riparian evapotranspiration. The extent to which these processes have an effect on a given region depends heavily on the climate, geology, and topography of the region. In addition to the physical processes, human consumption of available surface water and groundwater must be considered, especially in arid and semi-arid regions where supplies are limited and fully appropriated. Strategies for water management including man-made structures (dams, reservoirs, drains, canals, etc.) add more complexity to the system. Thus, to adequately quantify groundwater - surface water interaction, man-made structures and processes such as groundwater withdrawals and surface water diversions must be taken into account.

The sustainability of human populations and irrigated agriculture in arid regions, with highly variable climate and surface water flows, is dependent on well planned management of water resources, which in turn requires a thorough understanding of the physical processes that govern water movement (Tidwell et al., 2004; Sallenave and Cowley, 2004). Physical process and operational management alternatives can be evaluated using hydrologic system models, and in regions where surface water and groundwater interaction is significant, it is important to be able to adequately represent the exchange between the two regimes. An example of such an arid region with an expanding population and widespread agriculture is the Middle Rio Grande Basin in New Mexico. In this region water managers operate multiple man-made river structures that provide support for flood control and storage to meet downstream demands. A couple examples of surface water demands in the region include irrigation diversions and in-stream flow requirements which sustain endangered species.

To date, the amount of water needed to sustain environmental flows during times of drought in the Rio Grande Basin has been difficult to predict and the best strategies for retaining flows have yet to be identified (Cowley, 2006). Here, a better estimate of flow in the main river channel is needed so that more precise river operation policies can be developed for low flow conditions. Inadequate estimates of the interaction between surface and groundwater has been identified as a possible reason for the poorly predicted flows (Roark, 2007). As such, water managers need a tool that is able to simulate both the physical processes of flow and management objectives in order to meet demands. To fulfill this need, a linkage between two modeling tools, a surface water model RiverWare (Zagona et al., 2001; Zagona et al., 2005) and a groundwater model MODFLOW (Harbaugh et al., 2000; McDonald and Harbaugh, 1988) was proposed. This thesis documents the development and testing of a modeling framework linking RiverWare and MODFLOW, as well as a description of its application to the Middle Rio Grande.

1.1 Middle Rio Grande Basin Site Background

The Rio Grande flows approximately 1,885 miles, from its headwaters in the Colorado San Juan Mountains, through New Mexico, Texas, and Mexico before emptying into the Gulf of Mexico (Kernodle et al., 1987 and United States Geologic Survey [USGS], 1998). The Rio Grande Basin spans 182,200 square miles and is divided into multiple subbasins (Figure 1.1). The Middle Rio Grande Basin, one subbasin of the Rio Grande, is located in central New Mexico (Figures 1.2 and 1.3). More than 10 million people inhabit the Rio Grande Basin (USGS, 1998) and approximately 690,000 of them occupy the Middle Rio Grande region (McAda and

Barroll, 2002). The Middle Rio Grande Basin encompasses parts of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola Counties with the city of Albuquerque as the largest population center. Other communities in the Middle Rio Grande Basin include Rio Rancho, Los Lunas, Belen, Corrales, Bernalillo, Bernardo, and Isleta (Bartolino and Cole, 2002). In the Middle Rio Grande Basin, a system of drains and canals spreads laterally away from the river (McAda and Barroll, 2002). These structures were created to support agriculture (McAda and Barroll, 2002) and currently there are approximately 55,000 irrigated acres of agricultural land in the region (Gensler et al., 2007). The location of the Middle Rio Grande Basin boundaries varies depending on the source quoted. Either the basin extends from Cochiti to San Acacia or from Cochiti to Elephant Butte. The main sources (McAda and Barroll, 2002; Thorn et al., 1993; and Kernodle et al., 1995) referenced in this document define the basin boundaries as Cochiti to San Acacia. Thus, the use of the term Middle Rio Grande Basin in this document refers to the region between Cochiti and San Acacia. This region is also sometimes referred to as the Albuquerque Basin.

Figure 1.1) Rio Grande Basin (figure taken from USGS, 1998).

Figure 1.2) Location of the Middle Rio Grande Basin in New Mexico (figure taken from McAda and Barroll, 2002).

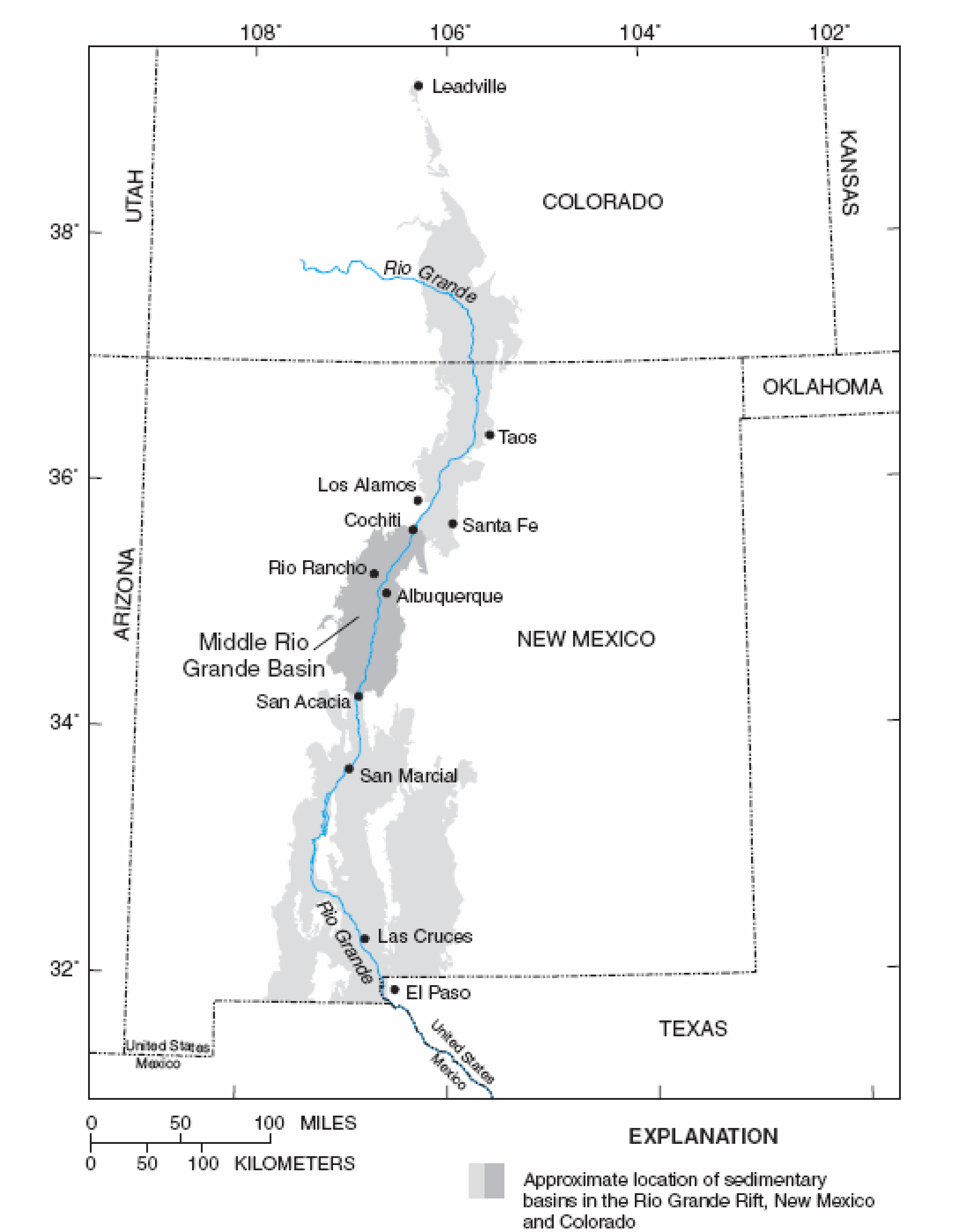
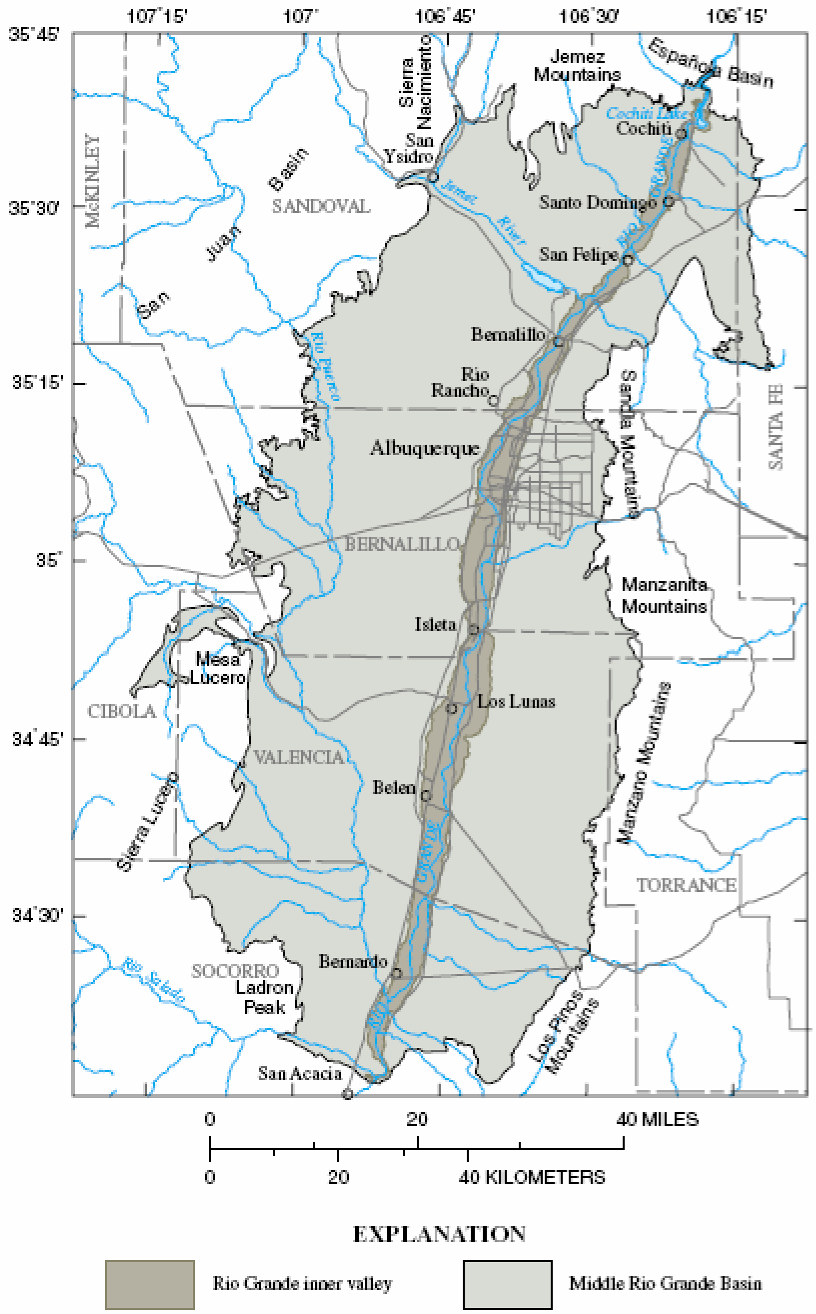


Figure 1.3) Major Physiographic Features of the Middle Rio Grande Basin in New Mexico (figure taken from Bartolino and Cole, 2002).



The Middle Rio Grande Basin is a desert landscape where surface water and groundwater interaction is of particular interest due to a great degree of water movement between the two regimes (Bartolino and Cole, 2002). The canals and drains of the irrigation system, as well as riparian evapotranspiration, have a strong influence on groundwater-surface water interaction in the region (McAda and Barroll, 2002). The following subsections describe the climatic, geologic, hydrologic, and ecologic features of the Middle Rio Grande Basin. Additionally, summaries of previously published surface water and groundwater models for the region are provided.

1.1.1 Climate

Climate in the Middle Rio Grande Basin is semi-arid, with mean annual precipitation observed from 7.9 to 12.2 centimeters per year, depending on location in the basin (Dahm et al., 2002). Annual precipitation values of 3.29 to 15.88 inches (Thorn et al., 1993), with a mean of 8.67 inches (Western Regional Climate Center [WRCC], 2005) have been recorded for the City of Albuquerque. The mean annual temperature also varies by location and ranges from 38 to 56 degrees Fahrenheit (Thorn et al., 1993). The Middle Rio Grande Basin has been defined as a desert and historically droughts have occurred in the region every 20 to 70 years (Cleverly et al., 2006). Recent droughts occurred in 1942 -1956, 1976-1977, and 2000-2006. The predominant surface water supply for the Rio Grande is snowmelt and scattered summer monsoon thunderstorms (Ward et al., 2006). These recent droughts and declines of up to 11 percent of mountain snow-pack (as discussed further in subsection 1.1.5) (New Mexico Drought Task Force, 2006) may be signs of a predicted drying trend in the region (Seager et al., 2007).

1.1.2 Geologic Features

The Middle Rio Grande Basin spans an area of approximately 3,060 square miles (Figures 1.2 and 1.3). The Middle Rio Grande Basin or depression is one of the largest basins formed by the Rio Grande Rift. The rift may be described as a set of North-South trending basins created by crustal extension (Thorn et al., 1993). The northern boundary of the Middle Rio Grande Basin is defined by the Jemez and Nacimiento uplifts at an elevation of roughly 6,500 feet above sea level. The Eastern boundary is defined by the Sandia, Manzano, and Los Pinos uplifts. The Western boundary, by far the most subdued boundary, is defined by the Rio Puerco Fault Zone and the Lucero Uplift. The southern boundary of the Basin near San Acacia is bounded by the convergence of the Eastern and Western boundaries and is at an elevation of roughly 4,500 feet above sea level (McAda and Barroll, 2002 and Thorn et al., 1993).

Sedimentary fill in the Middle Rio Grande Basin was deposited as the rift separated (Thorn et al., 1993). Middle Tertiary to Quaternary Santa Fe Group sediments constitute the majority of fill in basin and comprise the Santa Fe Aquifer system. Hawley and Haase (1992) divide the 14,000 thick Santa Fe Aquifer system into three zones: upper, middle, and lower (McAda and Barroll, 2002). The upper zone is up to 1,500 feet thick and contains the primary water bearing unit. These water yielding sediments are marked by intertonguing basin-floor fluvial deposits (ancestral Rio Grande Channel) and pediment-slope alluvial deposits (Sandia Mountains) which display anisotropic properties (McAda and Barroll, 2002 and Thorn et al., 1993).

1.1.3 Surface Water Features

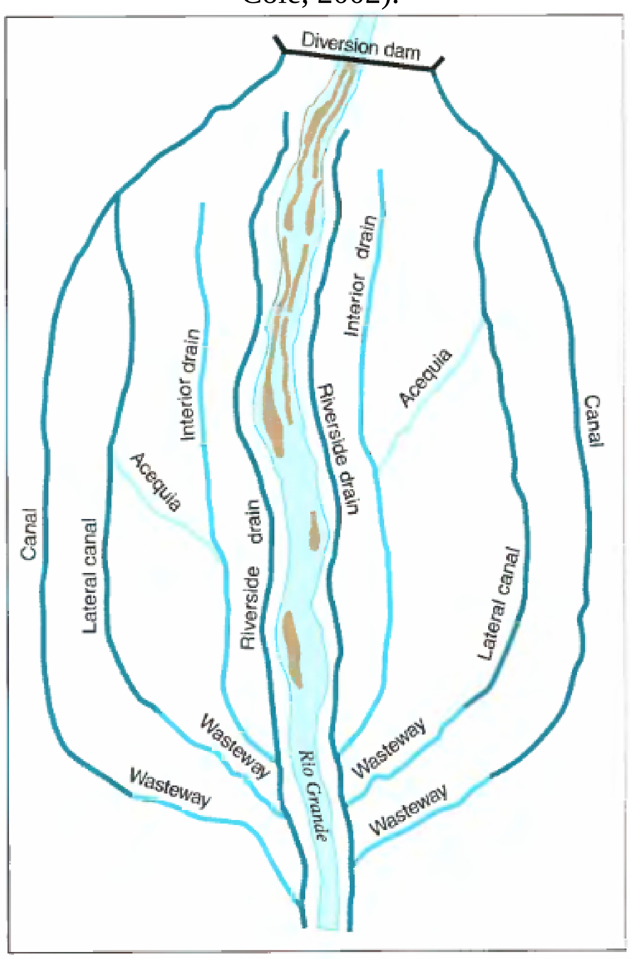
The Rio Grande is the fifth largest river in North America. It is a perennial stream in which some reaches may go dry during years of drought. The Rio Grande constitutes the greatest surface water inflow to the Middle Rio Grande Basin with an annual inflow of approximately 1,000,000 acre-feet. The largest tributary to the Rio Grande in the middle valley is the Jemez River with an average inflow of approximately 45,000 acre feet, annually. Additional ephemeral tributaries within the basin include the Santa Fe River, Galisteo Creek, Tijeras Arroyo, Abo Arroyo, Rio Puerco, and Rio Salado (McAda and Barroll, 2002). The basin is extensively irrigated. It is estimated that 30 to 40 percent of water consumption is for agriculture (Shafike, 2008) with the Rio Grande noted as the principal irrigation water source (McAda and Barroll, 2002). The Middle Rio Grande Conservancy District manages agricultural water distribution in the basin using a network of 1230 kilometers of canals, laterals, and ditches (Tidwell et al., 2004).

The Rio Grande valley is wide with a relatively narrow floodplain. Channel bank stabilization and floodway constriction measures have been implemented to prevent lateral river migration throughout the basin. Essentially, the natural course of the river has been restricted, and in the Albuquerque region portions of the river have become completely disconnected from the historical floodplain (SWCA Environmental Consultants and New Mexico Interstate Stream Commission [NMISC], 2007).

Man made river flow management structures in the Middle Rio Grande Basin include reservoirs, flood retention dams, and a system of irrigation canals and drains.

The reservoirs include: Cochiti Lake, Jemez Canyon Reservoir, and Galisteo Reservoir; the flood retention dams are located near Albuquerque and Rio Rancho; and the system of irrigation canals and drains span laterally away from the main river channel (Figure 1.4). River flow is diverted for irrigation at four main points within the Basin located at Cochiti Dam, Angostura, Isleta, and San Acacia (Figure 1.3). In addition to natural tributary inflows other sources of inflow (returns) to the main river channel include: treated wastewater from the cities of Bernalillo, Rio Rancho, Albuquerque, Los Lunas, and Belen; irrigation diversion return flows; and canal/drain inflows (see further discussion below) (Bartolino and Cole, 2002).

Figure 1.4) Example Depiction of the Middle Rio Grande Irrigation Network. Riverside drains and irrigation canals are shown (figure taken from Bartolino and Cole, 2002).



In the early 1900's, leaky unlined irrigation canals, applied irrigation, river seepage and river channel aggradation from extensive diversion created water-logged soil conditions in the Rio Grande valley. Interior and riverside drains were installed along the Rio Grande as part of the solution to mitigate the water logged soils (Thorn et al., 1993). An example depiction of the drains and canals in the region is shown in Figure 1.4. When constructed, the drain beds were at an elevation less than the shallow groundwater heads and were in direct contact with the aquifer. The intent of the drains was to intercept seepage from the main river channel or leakage in regions of applied irrigation and/or canals. The drain design allows collected flow to be returned into the main river channel at a few locations (McAda and Barroll, 2002). In the past few decades extensive groundwater pumping has led to declining groundwater levels (S.S. Papadopulos and Associates and NMISC, 2005) and the elevation of numerous interior drains is now higher than shallow groundwater heads. Therefore, many interior drains no longer serve their intended purpose. Currently, during the irrigation season, portions of the riverside drains and some interior drains are utilized as conveyance channels (McAda and Barroll, 2002).

1.1.4 Groundwater Features

Thorn et al. (1993) describe the Santa Fe Group aquifer system as ranging in thickness from 2,400 to 14,000 feet, with thickness increasing towards the center of the basin. The greatest water bearing unit is the upper zone of the Santa Fe Group which ranges from approximately 1,000 to 1,500 feet in thickness. Up to two-hundred feet of newer valley fill overlays the Santa Fe Group sediments and functions as the hydraulic connection between the surface and the Santa Fe Group aquifer

(Thorn et al., 1993). These upper 150 to 200 feet of sediments are referred to as the shallow aquifer (S.S. Papadopulos and Associates and NMISC, 2005) with the sections beneath referred to as the deep aquifer. Overall groundwater flow is from the boundaries towards the center of the basin where it trends southwest (McAda and Barroll, 2002). Within the middle Rio Grande, the two largest rivers, the Rio Grande and Jemez, are predominantly losing reaches, and thus the main source of recharge to the aquifer system. However, there are some regions in the basin where the aquifer discharges to the river. In these reaches surface water and groundwater interaction is complex and has been difficult to quantify. Additional groundwater recharge and discharge sources in the basin include canals, irrigated agricultural land, reservoirs/lakes, subsurface recharge from adjacent basins, precipitation, mountain front recharge, tributary recharge, and riparian evapotranspiration (McAda and Barroll, 2002).

Groundwater in the Middle Rio Grande Basin is primarily utilized as a water source for municipalities and industries. Municipal withdrawal includes well fields located in the cities of Bernalillo, Rio Rancho, Albuquerque, Bosque Farms, Los Lunas, and Belen. Additionally, several smaller communities utilize shared well fields, such as the Mutual Domestic Water Consumers Associations; some pueblos have well fields; and some single family households have domestic wells. For industrial use, several corporations have their own wells, with Intel being the largest consumer of this type (Bartolino and Cole, 2002). By far the city of Albuquerque is the largest consumer of groundwater (McAda and Barroll, 2002), withdrawing about 100,000 acre-feet annually (Shafike, 2008).

1.1.5 Climate Change Concerns

There is increasing concern that anthropogenic climate change will likely have adverse effects on the available water supply in the Southwestern North America. A recent study which analyzed multiple climate models predicts that a drying trend in the American Southwest has already begun and is expected to continue throughout the century (Seager et al., 2007). Seager et al's (2007) discussion focused on the rate of change of precipitation minus evaporation over the region in the various models which, overall, concluded a decrease in the rate. Future projections are based on global scale changes in humidity (a humidity increase due to increasing atmospheric temperatures which reduces moisture divergence over the subtropics) and atmospheric circulation patterns. In the Rio Grande Basin the climatology record from 1960 to 2000 was examined, and with moderate-to-strong confidence it was found that warming is occurring January to March and that spring streamflow has increased substantially (Hall et al., 2006). In a report compiled by the New Mexico Office of the State Engineer/Interstate Stream Commission (2006), snowpack in the Rio Grande Basin was found to be below average for 10 out of 16 years (1990 through 2006). These conditions could be indicative of a possible warming trend.

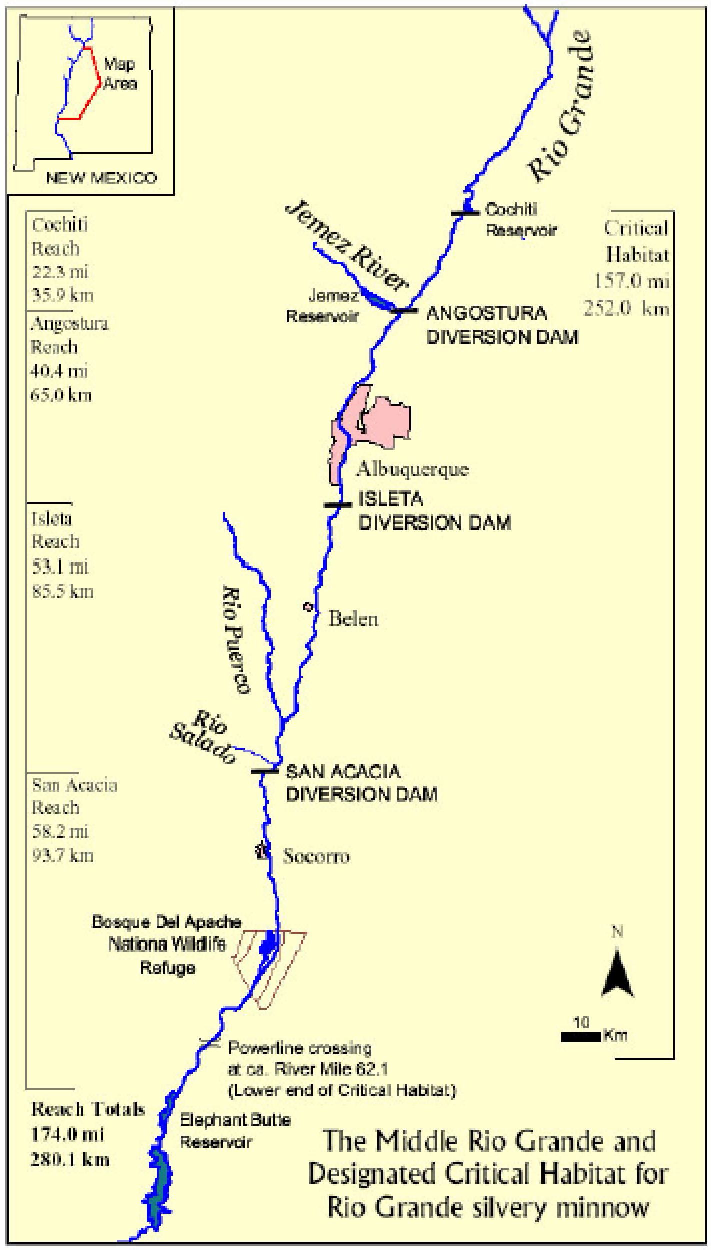
Panagoulia and Dimou (1996) looked at the sensitivity of groundwater-streamflow interaction to climate change in a central mountain catchment in Greece with similar climate as seen in parts of the American Southwest. They utilized a soil moisture accounting model based on mass balance tracking of percolation and soil moisture storage coupled with a snow accumulation and ablation model to show that snowmelt and runoff changes from increasing temperatures had a significant effect on groundwater surface water interaction. They found that increasing temperatures tended to shift peak water distribution to earlier in the year, for instance to February instead of April, and that decreased precipitation and increased temperatures produced lower levels of groundwater storage and streamflow, especially in summer and fall months. They concluded that surface-groundwater interaction was affected by temperature changes. In particular, they found that a seasonal shift in snow accumulation (caused by increased temperatures) yielded a higher groundwater to stream flow ratio. Observations by Hall et al. (2006) note a shift in spring runoff has already begun in the northern portions of the Rio Grande Basin, thus this seasonal shift may have an impact on groundwater surface-water interaction in the Basin. Hall et al. (2006) also state that seasonal timing and amplitude changes in streamflow could affect the region both economically and environmentally.

1.1.6 Ecological Concerns

The Rio Grande Silvery Minnow classified in the genus *Hybognathus* species *amarus* (U.S. Fish and Wildlife Service, 2007) was listed as endangered 1994; it is a pelagic spawner that inhabits the Rio Grande (SWCA Environmental Consultants and NMISC, 2007) in the 174 mile stretch between Cochiti Reservoir and Elephant Butte Reservoir, which is approximately 7% of the region it was known to historically occupy from the confluence of the Rio Chama to the Gulf of Mexico (U.S. Fish and Wildlife Service, 2007) (Figure 1.5). The Rio Grande silvery minnow once was one of the most abundant species in the Rio Grande and since being classified as endangered, the population continued to decline. Its remaining habitat is divided into four sections by three dams: Angostura Diversion Dam, Isleta Diversion Dam, and

San Acacia Diversion Dam (Figure 1.5) (U.S. Fish and Wildlife Service, 2007). The decreasing silvery minnow population is related to habitat modifications due to the addition of river management structures (e.g. dams, canals, and levees) which prevent upstream and downstream movement (U.S. Fish and Wildlife Service, 2002) and have altered the magnitude and variability of flow including increased and prolonged desiccation events and decreased peak-flow events. Additionally, during low flow periods pollutants from municipal and agricultural discharge are found to be elevated relative to periods of average flow, and these elevated concentrations adversely affect the Rio Grande silvery minnow. It is found that the Rio Grande silvery minnow tends to occupy portions of the river that have low to moderate water velocity, and high-flow events in May or June (e.g. spring runoff and summer storms) trigger it to release its semi-buoyant, non-adhesive eggs over approximately a three day period. Spiked releases from Cochiti Reservoir have also been found to trigger spawning (U.S. Fish and Wildlife Service, 2007). Lack of water has been defined as the "single most important limiting factor for the survival of the species" (U.S. Fish and Wildlife Service, 2002). Estimates suggest at least 50 cubic feet per second (cfs) of streamflow is needed to sustain the species and current federal mandates require 0 to 100 cfs depending on the type of hydrological year in the San Acacia reach (U.S. Fish and Wildlife Service, 2003). River capsucker, flathead chub, common carp, western mosquitofish, and red shiner are a few of the 21 native species of fish found in the New Mexico portion of the Rio Grande. It is estimated that several additional species have been extirpated from this stretch of the river (SWCA Environmental Consultants and NMISC, 2007).

Figure 1.5) Rio Grande Silvery Minnow Habitat (figure taken from U.S. Fish and Wildlife Service, 2007)



Alterations to natural seasonal flows have had a negative effect on native species and riparian vegetation throughout the southwestern United States (Cowley, 2006). One example was observed in the Cosumnes River in California where fall season flows have decreased over the past few decades. These low river flows are a likely contributor to the declining Chinook Salmon population since they occur at the height of spawning season (Fleckenstein et al., 2004). Fleckenstein et al. (2004) suggest that low flows are caused by the disconnection of the Cosumnes River and the underlying aquifer, a common consequence of artificially lowered groundwater levels (Sophocleous, 2002). Fleckenstein et al. (2004) present several scenarios for maintaining and/or increasing fall season flows and it was determined that long term groundwater and surface water management strategies are necessary to improve river conditions. Their recommendation for an immediate and future increase in fall season flows combines reduced year round pumping and seasonal surface water augmentations.

In addition to aquatic species many amphibians, reptiles, mammals, and birds rely on the Rio Grande and inhabit its riparian corridor (SWCA Environmental Consultants and NMISC, 2007). Herbaceous and shrubby vegetation predominate the riverbank ecosystems. Native and non-native invasive species are present including cottonwood, willow, sleep willow, New Mexico olive, Russian olive and salt cedar (U.S. Army Corps of Engineers [USACE] et al., 2007). Distribution and composition of vegetation in these regions is influenced by the quantity of water available. Shallow groundwater and seepage from the river support these habitats. Over the past century the density of riparian vegetation has continually increased due to anthropogenic modifications along the river corridor (Cleverly et al., 2006). Several researches have estimated the annual uptake of groundwater by riparian evapotranspiration in the Middle Rio Grande Basin at values ranging from 75,000 to 195,000 acre-feet (McAda and Barroll, 2002), and it has been stated that about twothirds of the surface water consumption in the basin is from open water surface evaporation and riparian evapotranspiration (Bartolino and Cole, 2002). Thus, evapotranspiration constitutes a major component in the water budget of the region.

Seepage from unlined irrigation ditches along the Rio Grande was measured near Alcalde in Northern New Mexico by Fernald and Guldan (2006), and a consistent seasonal pattern of elevated shallow groundwater levels were observed during the irrigation season. They found approximately 5% of flow from the unlined ditches seeped to the shallow aquifer, except in the near vicinity of the Rio Grande. In the near vicinity of the Rio Grande (approximately 60 meters from the river) shallow groundwater levels were less effected by the onset of the irrigation season, suggesting additional factors such as evapotranspiration and river interaction have a great influence on shallow aquifer levels in the riparian corridor. In southern New Mexico between Socorro and San Antonio, river management alternatives have been tested including the type of riparian vegetation present and alteration of existing canal/drain system effects on river seepage, with a goal of optimizing Rio Grande conveyance and in-stream flows (Wilcox et al., 2007). The effects of reduced riparian evapotranspiration were tested using a MODBRANCH model (see Section 2.1.1.1 for MODBRANCH description). A reduction of 50% from current (year 2000) evapotranspiration rates produced a decrease of approximately 6% of river seepage, while lesser evapotranspiration reductions of 5% and 20% produced a less significant decrease to river seepage of 1-2%. Again using a MODBRANCH model the effects of filling in the LFCC (Low Flow Conveyance Channel) which currently acts as a riverside drain (no water is diverted into this channel from the river) were tested. River seepage was significantly decreased by the removal of the LFCC (67-72% reduction), however the desired result of increased water conveyance was not met and an additional undesired effect of water logged soils downstream was produced.

1.1.7 River Management

Rio Grande managers are confronted with challenges faced by many arid regions throughout the world: increasing demands, limited water supplies, and over-allocation of the existing water supply (Ward et al., 2006). In a system that has fully appropriated its water, understanding the physical processes that govern its movement is crucial. The primary goals of river management are daily operations and future planning including flooding and droughts. Insuring system stability in times of drought is a high priority and rightly so, with drought occurrence and severity likely to increase in the region due to a changing climate (Ward et al., 2007).

In New Mexico several state and federal agencies share the responsibility of managing water resources in the basin: the New Mexico Office of the State Engineer and Interstate Stream Commission; the Bureau of Reclamation, USACE, and local Pueblos. Surface water flow in the basin is considered fully appropriated, with the Rio Grande Compact as the main governing legal contract. The Rio Grande Compact is a multi-state agreement between Colorado, New Mexico, and Texas for water allocation. As described in subsection 1.1.3 multiple river management structures exist along the Rio Grande and coordinated operations are needed to ensure water demands are met. River managers have used many different modeling schemes to track and quantify the water budget in the region and a description of existing operational and physical process models, as well as a discussion of economic model findings for the Basin, are provided below.

Specific surface water management priorities and goals along the Rio Grande include: flood and sediment control; fish and wildlife enhancement; recreation; diversion and delivery of irrigation and municipal water; power generation; Native American water rights; water storage; storage and delivery of San Juan Chama water; and Rio Grande Compact delivery requirements (U.S. Fish and Wildlife Service, 2008).

1.1.7.1 Middle Rio Grande Operational and Physical Process Models

The USGS has completed multiple reports and several government agencies have developed groundwater and surface water models of the Rio Grande Basin. For analyzing groundwater flow in the basin the USGS developed and has continually updated the Middle Rio Grande Regional Groundwater Model (Kernodle et al., 1987; Tiedeman et al., 1998; and McAda and Barroll, 2002) (Figure 1.6). The model is intended as a tool to help water managers quantify available groundwater resources with in the basin. From here on this model will be referred to as the Regional Groundwater Model. The Regional Groundwater model uses MODFLOW to model flow within the Santa Fe Group aquifer and valley fill deposits. MODFLOW is a three-dimensional, numeric, finite difference, porous medium flow model. At its core, MODFLOW is a porous medium flow solver which contains several finite-difference solution methods to the groundwater flow equations. Multiple hydrologic processes can be incorporated into the basic groundwater flow equations, such as aquifer withdrawals, surface water gain/loss, and evapotranspiration. The Regional

Groundwater model spans from Cochiti to San Acacia and extends up to 9,000 feet in depth. Nine layers are used which represent changing aquifer properties with well production predominately from the top five layers. Additionally, several future projection scenarios have been examined using the Regional Groundwater Model (Kernodle et al., 1995; Bexfield and McAda 2001; and Bexfield et al., 2004).

For managing surface water in the basin the USACE, Bureau of Reclamation, USGS, several other federal agencies, and the NMISC have created and maintained the Upper Rio Grande Water Operations Model (URGWOM) (USACE, 2007) (Figure 1.7) which is written in the modeling program RiverWare. The URGWOM's main functions are long-term planning and evaluation of operations, seasonal forecasting, and day to day river and reservoir operations, including water accounting. Current river operations managers use URGWOM to help determine their release and delivery schedules along the Rio Grande. RiverWare is a surface water object oriented physical process model that employs user selectable algorithms to represent each desired physical process. RiverWare is a tool created to help manage basin wide water allocations in river systems containing management structures (e.g. reservoirs and diversion dams). RiverWare contains features for: reservoir storage and release operations; hydropower management; water right and allocation priority rankings (i.e. law of the river); parameter optimization; and seasonal forecasting. The URGWOM models the region from Colorado-New Mexico state line to Elephant Butte Reservoir.

While both the URGWOM and Regional Groundwater Model have been in use for nearly a decade, in the past couple of years a set of riparian-zone groundwater models were developed by S.S. Papadopulos and Associates and NMISC (2005 and

2007). These high resolution MODFLOW models are more refined than the Regional Groundwater Model and span small sections of the river corridor (Figure 1.8). The riparian models are similar to the Regional Groundwater Model since they were created using some of the same data sets as the Regional Groundwater Model and outputs from the Regional Groundwater Model have been incorporated as boundary conditions in the Riparian models. These models were developed to evaluate shallow groundwater conditions in specific river reaches from Cochiti to Elephant Butte Reservoir for purposes of habitat restoration and river management.

Figure 1.6) Middle Rio Grande Regional Groundwater Model (taken from McAda and Barroll, 2002)

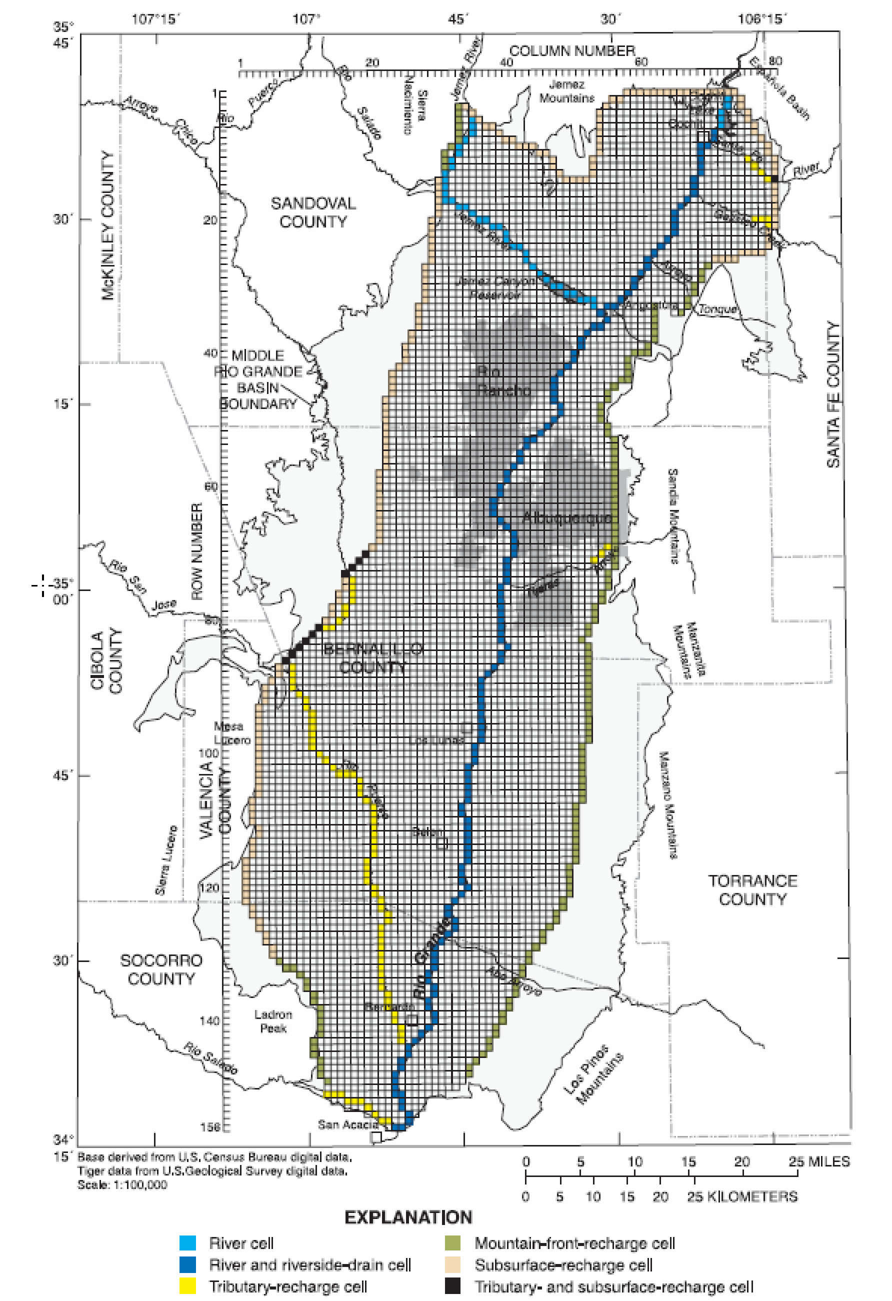


Figure 1.7) URGWOM RiverWare Model

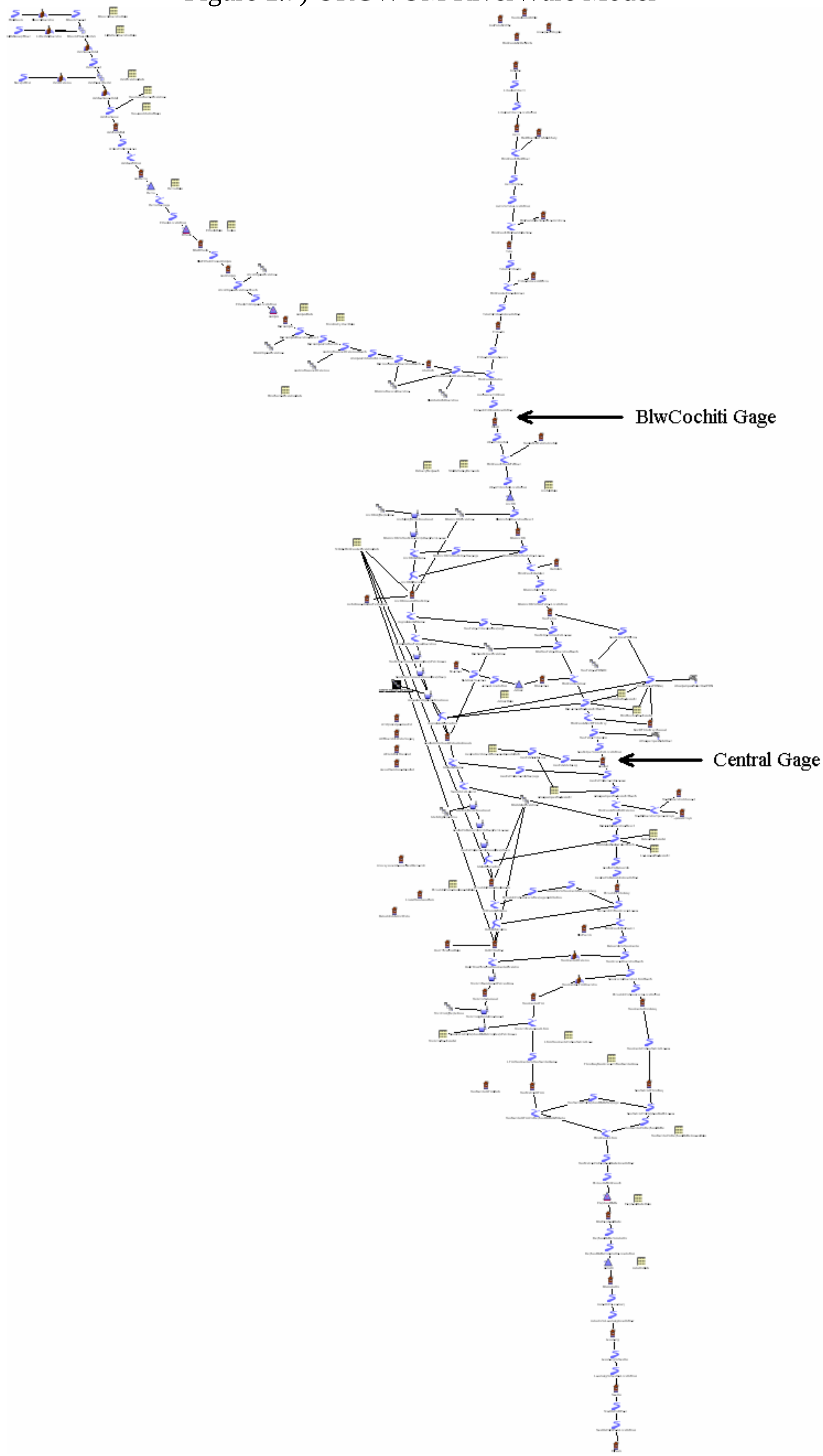
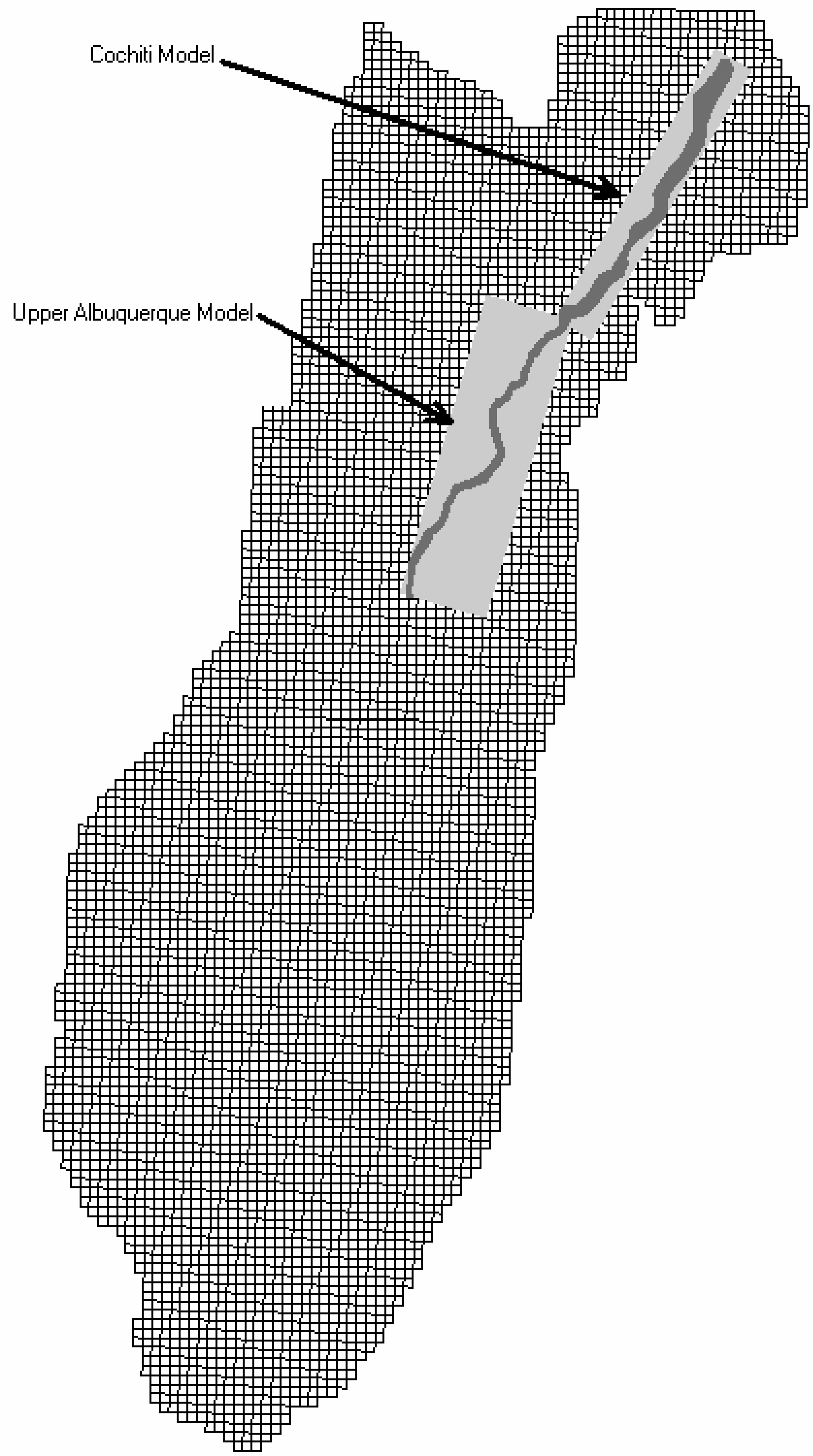


Figure 1.8) Riparian Groundwater Models Overlain on the Regional Groundwater Model. Active model grid is shown for the Regional Groundwater Model, the full model boundaries are shown for the Cochiti and Upper Albuquerque riparian models in light gray and the active boundaries are shown in dark gray.



1.1.7.2 Middle Rio Grande Economic Models

Several studies have been undertaken for regions in the southwestern United States that address declining flows and forecasted droughts from an economic or cost network perspective. Ward et al. (2007 and 2006) suggest that water conservation initiatives tend to be directly linked with the price of water and that economic damages due to drought conditions could be mitigated by cooperative institutional water marketing between states. There is a need for models that are able to accurately incorporate institutional, environmental, and physical processes. Tidwell et al. (2004) present a planning model that uses systems dynamics or a set of cost-and-effect relations to model water budget in the Middle Rio Grande region. They found that if no conservation actions are taken, the rate of groundwater depletion in the basin increases with time and a deficit accrues when attempting to meet Rio Grande Compact obligations. While economic models are able to explore water management alternatives in terms of cost, they are not capable of addressing the physical flow processes in localized regions to adequately suggest quantities needed to meet flow targets necessary to protect endangered species and habitat.

1.2 Rationale for Creating the RiverWare-MODFLOW Link

A link between RiverWare (Zagona et al., 2001; Zagona et al., 2005) and MODFLOW was predicated on the basis that surface water-groundwater interaction in the Middle Rio Grande Basin have not been adequately addressed by existing models. The idea stemmed from a need to better predict when and where low flows will occur along sections of the Rio Grande near Albuquerque, New Mexico. The connection between the river and the aquifer has a significant effect on the quantity of water in the main channel of the Rio Grande and water managers have had a difficult time predicting how much water needs to be released from the Cochiti Reservoir in order to maintain flow in certain sections of the Rio Grande.

The current river operations model (URGWOM) employs the modeling program RiverWare (see section 1.1.7 for a description of URGWOM and RiverWare). While RiverWare is a good surface water management tool, it is not well suited to model the interaction between surface water - groundwater or the small scale drains and canals present in the basin, due to their small size, large number, and/or lack of detailed information needed to support these tasks. To rectify this inadequacy, a proposal was made to link RiverWare with MODFLOW. MODFLOW was selected for this linkage for several reasons: it is a public domain model; it was developed so that users with specific needs can easily incorporate new capability into the system without requiring significant changes to the existing core code; and the current groundwater flow models for the Rio Grande Basin were constructed using MODFLOW.

1.3 Linked Model Objective

The basic intent of the linked model is to accurately model a river corridor and aquifer beneath, including surface water features (e.g. canals, drains, reservoirs) and surrounding riparian zone, incorporating both natural and human water consumption from a management perspective. The reasoning behind linking a previously well-established groundwater model (MODFLOW) with a surface water model (RiverWare) is to allow each model to handle the processes for which it was designed. It is hoped that by providing water managers with a tool that is able to simulate both the physical processes of groundwater-surface water flow, water user demands and associated management objectives, they will be able to adequately quantify surface flow releases needed during drought periods to meet given downstream targets.

1.4 Thesis Outline

The following chapters contain a literature review on groundwater-surface water interaction modeling (Chapter 2), a description of the RiverWare-MODFLOW Link (Chapter 3), and several Case Studies using the RiverWare-MODFLOW linked model (Chapter 4), and summary and conclusions (Chapter 5).

CHAPTER 2 – LITERATURE REVIEW

The most basic interpretation of surface water-groundwater interaction can be described by the direction of flux between a surface water body and the underlying aquifer. Stream reaches may be defined as losing, gaining, or parallel-flow depending on the elevation difference between stage in the stream and the head in the aquifer. It should be noted that many in-stream processes are affected by these interactions such ecological and geochemical processes. However these processes are beyond the scope of this work and will not be discussed. Instead the reader is directed to Sophocleous (2002) and Woessner (2000) who provide detailed descriptions of groundwater surface water interactions and the processes involved, along with summaries of available literature on the subject.

This chapter focuses on currently available groundwater-surface water interaction models, a variety of which are available to water resource managers. Some basic application considerations must be made when selecting an appropriate model for a project. For instance, what is an acceptable temporal duration and resolution, spatial dimension, and model solution method (numerical, analytical, physically based, or data driven)? Various configurations are available for coupling surface water-groundwater interaction. First, one model could be incorporated into another or two modeling programs could be run independently. Second, in either model combination configuration several approaches have been taken to facilitate data exchange between the two processes (groundwater flow and surface-water flow): they may be run sequentially with data output from the first process used as input in the second; they may be run in parallel with data exchanged either between time-steps or by iterative coupling; or they may be intrinsically coupled.

2.1 Coupled Surface Water-Groundwater Models

2.1.1 Physical Process Models

Many of the coupled models discussed in this section model subsurface flow using MODFLOW, thus a description of this model is provided here. MODFLOW is a widely used public domain model distributed by the United States Geologic Survey (USGS). As described in Chapter 1, MODFLOW is a three-dimensional, numeric, finite difference, porous medium flow model. It contains a porous medium flow solver with several finite-difference solution methods for the groundwater flow equations, into which multiple hydrologic processes may be incorporated. MODFLOW's formulation allows these hydrologic processes to solve independently but simultaneously; thus the model is able to represent various combinations of hydrologic processes at one time. The MODFLOW software was developed to be adaptable, so users with specific needs would be able to incorporate new capabilities into its framework without requiring significant changes to the existing core code (Harbaugh et al., 2000; McDonald and Harbaugh, 1988). Several of the groundwater-surface water interaction models discussed in this chapter detail user additions to MODFLOW. Some of these non-standard functions/packages were prepared by the USGS itself, but were not incorporated into the standard version of MODFLOW. These include DAFLOW-MODFLOW (Jobson and Harbaugh, 1999) and MODBRANCH (Swain and Wexler, 1996). The standard MODFLOW 2000 release does contain several options for modeling surface water features such as lakes, streams, and land-surface recharge and their interaction with the underlying aquifer. The river/stream packages, *STR*, *SFR*, and *SFR2* (Prudic, 1989; Prudic et al., 2004; Niswonger and Prudic, 2005) available in MODFLOW 2000 focus on saturated and unsaturated flow and route surface channel flow as uniform and steady. The connection between the stream and aquifer in all three packages is modeled using Darcy's Law across the streambed (Prudic, 1989; Prudic et al., 2004; Niswonger and Prudic, 2005).

2.1.1.1 Groundwater and Surface Channel Flow Models

Two models developed by the USGS, DAFLOW-MODFLOW and MODBRANCH, employ more advanced channel routing methods than the standard MODFLOW packages and contain an iterative time stepping approach for coupling the surface and subsurface interactions. Both models link surface and subsurface domains using a hydraulic gradient driven flux and assume a saturated subsurface domain. They both were created from existing surface water routing models and were restructured and incorporated into MODFLOW. Jobson and Harbaugh's (1999) DAFLOW (Diffusion Analogy Surface-Water Flow Model) employs a one dimensional diffusive wave approximation for in-channel flow while Schaffranek's (1987) BRANCH simulates unsteady, non-uniform flow in open channels using an implicit, weighted four point finite difference approximation for the dynamic wave equations. BRANCH is referred to as MODBRANCH when incorporated into MODFLOW (Swain and Wexler, 1996).

In most situations, the temporal scale for modeling groundwater and surface water systems is intrinsically different - groundwater response is typically modeled on a monthly, seasonal, or yearly time scale while surface water response for operational purposes is modeled on an hourly, daily or weekly timeframe. Limitations due to sparse availability of data for groundwater systems is also a time limiting factor. For example, in the case of Chiew et al. (1992), a monthly time-step was used for modeling the groundwater system because no data was available to support a shorter time-step.

Both DAFLOW-MODFLOW and MODBRANCH address the difference between surface and subsurface modeling time scales using an iterative approach, whereby the groundwater interval must be an integer multiple of the surface water time-step. The groundwater head at the beginning and end of a groundwater time-step is interpolated to obtain a head at the beginning of each surface water time-step within the interval. For a single groundwater time-step, the surface water and groundwater routines are repeated until the head and/or stage values compared between successive iterations fall below a given tolerance.

DAFLOW-MODFLOW was created to simulate flow in upland steams (Jobson and Harbaugh, 1999) and in their paper Jobson and Harbaugh stated that accuracy increases with increasing streambed slope. While Lin and Median (2003) use DAFLOW-MODFLOW in conjunction with MOC3D (a 3-D method-of-characteristics ground-water flow and transport model integrated in MODFLOW) and verify contaminant transport results from a tracer test preformed in a mountain terrain, there are few other published examples which use DAFLOW-MODFLOW. DAFLOW output is often used in water quality studies as input into BLTM, a contaminant transport model (Laenen and Risley, 1997; and Broshears et al., 2001).

Jobson and Harbaugh do provide several examples in their 1999 report that test the functionality of the DAFLOW-MODFLOW model. Their scenarios include: stream-flow resulting from variable recharge; bank storage from flood wave propagation; and bank storage due to unsteady flow. The first two scenarios use a 7.5 day time-step for both surface water and groundwater calculations and the third scenario employs unequal surface and subsurface time-steps with a surface water time-step of 15 minutes and a groundwater time-step that is 30 minutes. From the examples, it appears that a short time-step on the order of days is appropriate to model the surface and groundwater interactions using the DAFLOW-MODFLOW model, however this model is limited in the surface domain features beyond hydraulic routing and is best suited for modeling steep mountain catchments.

MODBRANCH has been used in several applications, most notably to examine the effects of raised water levels in the Florida Everglade on a neighboring residential community in Dade County (Swain et al., 1996). It was also applied in the Middle Rio Grande Basin to simulate the interaction between surface water and groundwater in the San Acacia reach (San Acacia to Elephant Butte Reservoir) (Shafike, 2005). The BRANCH portion of MODBRANCH was used to represent flow in several proposed canals, where the objective of the canals was to prevent soil water logging in the residential area. The surface water time-step of 12 hours is an even multiple of the 5 day groundwater time-step. This model, like DAFLOW-MODFLOW, is limited in surface water modeling capabilities beyond in-channel routing, and complex diversion driven operations cannot be represented. Additionally, MODBRANCH has not been well received by regulatory agencies due to poor performance (Tillery, 2006). Both MODBRANCH and DAFLOW-MODFLOW are freely available from the USGS.

MODHMS (Hydrogeologic, 1996) goes a step further than DAFLOW-MODFLOW and MODBRANCH in coupling surface and subsurface flow. MODHMS is a modified version of MODFLOW that solves a fully three dimensional saturated/unsaturated subsurface flow equation. Like DAFLOW-MODFLOW, MODHMS contains a one dimensional diffusive wave approximation for channel flow. Unlike DAFLOW-MODFLOW, it has an option to solve surface water-groundwater interactions using a fully implicit procedure and contains a two dimensional diffusive wave approximation for overland flow and adaptive time stepping. However, if unequal surface and subsurface timeframes are desired, an iteratively coupled solution similar to that used in DAFLOW-MODFLOW and MODBRANCH is employed. MODHMS is not freely available but is distributed by Hydrogeologic Inc. (Panday and Huyakorn, 2004; and Hydrogeologic, 1996).

MODHMS has been used for large scale basin-wide hydrologic modeling (Werner et al., 2006; Sedmera et al., 2004). Additionally it has been used to test management alternatives for water quality control due to seawater intrusion (Bajracharya et al., 2006; and Werner and Gallagher, 2006; and California Regional Water Quality Control Board, 2006). The Werner et al. (2006) model employs a daily time-step for modeling surface features and a monthly time-step for modeling the subsurface. The other authors did not state what time-step size was used in their models.

Some limitations of the MODHMS model have been identified by the authors noted above. Werner et al. (2006) ran several scenarios to test MODHMS's modeling accuracy and found that when a coarse model scale was used, the model's ability to reproduce stream flow processes in the riparian zone was limited. Werner et al. (2006) and Bajracharya et al. (2006) both encountered numerical errors stemming from the adaptive time stepping technique. As is the case with MODBRANCH and DAFLOW-MODFLOW, stream flow management/operation objectives cannot be represented in MODHMS.

Kollett and Maxwell (2006) present a surface water program coupled with a variably saturated subsurface system which is similar to MODHMS. They incorporate a two-dimensional distributed kinematic approximation of overland flow into an existing model, ParFlow, a parallel three-dimensional finite difference model for approximating variably saturated groundwater flow. A key difference between MODHMS and ParFlow is that, in ParFlow, an overland flow boundary condition is employed instead of a conductance term to bound the interface between surface and subsurface flow.

Parflow has been used in multiple groundwater modeling applications such as assessing groundwater level declines in an arid region (Abu-El-Shar'r and Rihani, 2007) and testing of contaminant transport remediation alternatives (Tompson et al., 1998). However, only one example using Parflow with the overland flow condition could be found: the Parflow model of Little Washita watershed in Oklahoma described by Chow et al. (2006) is additionally coupled to an atmospheric model (APRS). The model was run for a short duration of 48 hours with both surface and subsurface regimes in Parflow using an hourly time-step. Since the authors did not provide a detailed discussion of the surface/subsurface interaction, no conclusions can be drawn as to the performance of the model for this process. A drawback of the Parflow model, as has been previously discussed in terms of the MODLFOW models, is that surface water management strategies to meet human demands cannot be incorporated into the model.

2.1.1.2 Groundwater and Watershed Models

Ross et al. (1997) take a different approach to coupling surface and subsurface flow regimes, in that they look at the surface hydrologic system as a whole and use a watershed model in lieu of a channel routing model. Their model, the Florida Institute of Phosphate Research (FIPR) hydrologic model, FHM, simulates the hydrologic cycle with MODFLOW representing the subsurface domain and Hydrologic Simulation Program-Fortran (HSPF), a model developed by the Environmental Protection Agency, representing the surface domain. HSPF is a hydrologic and water quality model that simulates pervious and impervious surface flow using a lumped parameter approach. Parameters in the model include overland flow, channel flow, runoff, aquifer recharge, precipitation, and surface ET. FHM is essentially a shell program that runs HSPF and MODFLOW and contains a data exchange process which accommodates spatial and temporal differences between the two models. A time loop increment is set and the two programs run sequentially. HSPF runs first on an hourly or shorter basis for one pass through the loop; data is passed to MODFLOW; and MODFLOW is run for a daily or longer time-step for the same loop. The looping sequence is repeated until the desired model length is reached.

For the coupled models discussed thus far, spatial scale discrepancies between the surface and subsurface regimes have not needed to be addressed. HSPF represents the watershed as a collection of subbasins; the spatial extent of each subbasin is much greater than a single MODFLOW cell - in fact they span large regions of the MODFLOW domain. The spatial differences between the programs are handled in a similar fashion as the temporal difference, where data exchange between the two models is aggregated and disaggregated as necessary. While HSPF contains methods for tracking flow between surface and unsaturated subsurface domains, when a continuous simulation is run, flux between the surface and subsurface is calculated in MODFLOW using the stream or other conductance concept boundary packages.

FHM was used to evaluate the water budget in the Big Lost River Basin in Idaho (Said et al., 2005). The surface water - groundwater interaction in the basin are dynamic; it is noted that precipitation is the main source of groundwater recharge, and in turn the main water source for the stream is baseflow from the aquifer (Said et al., 2005). FHM has also been used to model wetland mitigation alternatives and ecosystem restoration in Saddle Creek in Florida (Tara et al., 2003). The models presented by Said et al. (2005) and Tara et al. (2003) both employ different time-step sizes for the surface and groundwater portions of the models. The first uses an hourly surface water time-step and a daily groundwater time-step, while the latter uses daily surface water and monthly groundwater time-steps (Said et al., 2005; and Tara et al., 2003). The FHM model design has multiple limitations including: a total of only 10 diversions can be simulated at one time; the MODFLOW model size must be less than 106 by 60 cells; and all the model simulations involving groundwater-surface water interaction must be less than one year in length (Ross et al., 1997).

Like FHM, SWAT (Neitsch et al., 2005) is a watershed scale model that simulates water budget using lumped parameter estimation and has been linked with MODFLOW to create SWATMOD (Sophocleous and Perkins, 2000). SWAT is a physically based model which represents a watershed as a group of subbasins. Lumped hydrologic equations are applied to each subbasin including soil, land use, and weather data. Alterations were made to MODFLOW's stream routing package (*STR*) to accommodate net surface inflows from SWAT. Spatial differences are a factor between the two models and a new MODFLOW package was written to associate data exchange between the SWAT subbbasins and MODFLOW cells. Additionally, SWAT was modified to accommodate a temporal difference between SWAT's daily time-step and larger time-steps on the order of months or a year used by MODFLOW (Perkins and Sophocleous, 1999; Sophocleous and Perkins, 2000). SWATMOD uses a time looping procedure similar to that used in FHM.

SWAT has been used mainly for modeling watersheds with a focus on the impacts of agricultural land use on water supplies, including pollution (Texas Water Resources Institute, 2007). SWATMOD has been applied to several sites in Kansas including Rattle Snake Creek and the Lower Republican River Basin (Sophocleous et al., 1999; and Sophocleous and Perkins, 2000). The goal of both models was to prevent future declines in the already stressed river system. While SWATMOD is good for modeling overall water budgeting within a basin the lumped structure of the surface water portion of the model is not be able to handle individual detailed river diversions, nor can it quantify localized groundwater surface water interaction due to stream/aquifer flux.

Another linked watershed model, developed by Chiew et al. (1992) employs a daily rainfall runoff model (Hydrolog) with limited stream routing capabilities. Hydrolog is integrated with AQUIFEM-N, a quasi three dimensional finite element model. As with FHM and SWATMOD, spatial and temporal differences exist between the two flow regimes and are coupled though summation and interpolation. The Hydrolog-AQUIFEM-N model was used in the Campaspe River Basin in north-central Australia to estimate fluctuating groundwater recharge. Surface processes were calculated at a daily time-step and subsurface on a monthly time-step. Like SWATMOD, Hydrolog-AQUIFEM-N is good for modeling the overall water budget within a basin, but the lumped structure of the surface water portion of the model cannot handle multiple river diversions and cannot quantify localized groundwater surface water interaction.

2.1.2 Operational Models

All the models described above incorporate the physical processes of the hydrologic cycle and were not designed to handle management and operational objectives for human demands. Operational management models like RiverWare were designed to handle management objectives like water allocation. As stated in Section 1.1.7.1 RiverWare is a surface water object oriented physical process model that employs user selectable algorithms to represent each desired physical process. RiverWare is a tool that facilitates management of basin wide water allocations in river systems containing water management structures (e.g. reservoirs and diversion dams). RiverWare contains features for: reservoir storage and release operations; hydropower management; water right and allocation priority rankings (i.e. law of the river); parameter optimization; and seasonal forecasting. Similar to RiverWare, StateMod, the State of Colorado's Stream Simulation Model, is a surface water resources allocation and accounting model. StateMod is capable of modeling hydrology, water rights, stream management structures (e.g. reservoirs), and operating rules (State of Colorado, 2004). StateMod is one component of Colorado's decision support system (CDSS), a database of hydrologic and administrative information developed by the Colorado Water Conservation Board and the Colorado Division of Water Resources (State of Colorado, 2007a). In StateMod a river basin is represented as a network of connected nodes for which each node represents items such as stream gauges, diversion structures, and reservoirs. The main components of the StateMod program include operational rules, return flows, in-stream flows, wells, base-flows, soil moisture accounting, and diversions. These components combined can be used for daily operations and future planning (State of Colorado, 2007b). Models can be set to run at a daily or monthly time-step. Two simplified groundwater flow mechanisms have been incorporated into StateMod: groundwater pumping wells and soil moisture accounting. Water from groundwater pumping wells can be set as inflow sources to surface water features such as diversions and river flow. Likewise, groundwater sinks such as return flows and river depletions may be set as surface losses to groundwater. The second feature, soil moisture accounting, allows for a store of water in the soil zone. The amount of water available in the soil zone can be controlled using operational rules and can supplement river-base flows (State of Colorado, 2007b). StateMod has been applied to the Colorado, Gunnison, Yampa, and San Jaun River Basins (State of Colorado, 2007a). The model's two groundwater features are accounting strategies for groundwater inflows/outflows to the surface water system and are limited since they do not model the actual physical process between the two regimes.

The California Water Resources Simulation Model (CalSim) also known as Water Resources Integrated Modeling System (WRIMS) is a reservoir-river basin simulation model which employs single time-step optimization (Draper et al., 2004). It can be used to model operational rules and water allocation by priority ranking. Like StateMod, CalSim uses a network of connected nodes where each node represents items (e.g. reservoir) in a stream system. Operational criteria are specified by weighted priorities within a system of rules and constraints. In CalSim groundwater is incorporated using a system of interconnected lumped-parameter basins whose features includes groundwater pumping, irrigation recharge, stream-aquifer interaction, and inter-basin flow. Draper et al. (2004) state that the representation of groundwater processes in CalSim is limited. CalSim has been utilized throughout California in projects such as the Central Valley Project (CVP) and State Water Project (SWP). The CVP-SWP system models employ a monthly time-step for applications such as hydrologic behavior, reservoir operations, hydropower, water quality, and irrigation.

Labadie and Baldo (2000), Fredericks et al. (1998), and Miller et al. (2003) present MODSIM, a basin-wide and regional river and reservoir operations tool that employs a minimum cost network flow algorithm satisfying hydrologic mass balance.

Like StateMod and CalSim, this surface water management model consists of linked nodes representing river features such as diversions, inflows, and reservoirs for which flow distribution can be prioritized to meet management objectives. Interaction of these features with an underlying aquifer can be incorporated into MODSIM using response functions generated by MODRSP (Miller et al., 2003) as infiltration and pumping nodes. The response functions allow transient aquifer recharge conditions to be incorporated into MODSIM. MODRSP is a modified version of MODFLOW that generates response functions representing aquifer stresses at each MODFLOW grid cell. The model was divided into zones based on the output response functions with each zone containing similar response functions, and each zone is then correlated to nodes in the MODSIM model.

The MODSIM model with MODRSP response functions has been applied to several situations involving conjunctive use of surface and groundwater supplies. The predominant historical use of water in the Snake River Basin was agricultural irrigation. A desire to increase river stage during low flow seasons to meet hydroelectricity, recreation, and ecological demands has been expressed (Miller et al., 2003). Similarly, in the South Platte River Basin increased groundwater pumping during irrigation season has negatively affected flow in the South Platte River (Fredericks et al., 1998) and a desire to stabilize and/or increase flows in the river have been expressed. In order to meet the increased flow demands, the MODSIM model with MODRSP was used on a monthly time frame to evaluate management alternatives though increased river diversions for artificial aquifer recharge during higher flow/less demand periods and their effect on river discharge during low flow/higher demand times (Miller et al., 2003, and Fredericks et al., 1998). While it was shown in both cases that groundwater recharge augmentation could be tracked using MODSIM with MODRSP, Miller et al. (2003) admits that that the response functions cannot be used to quantify riverbed/aquifer flux and both papers agree that the combined model is best suited for modeling regional basin scales.

While StateMod, CalSim, and MODSIM with MODRSP are good for modeling large scale surface water operational objectives and contain groundwater modeling features, none of them are well suited to quantify groundwater-surface water interaction in localized regions due to the limited scope of their groundwater features. Thus none of these models would be appropriate to address the requirements along the Middle Rio Grande.

2.2 Literature Review Findings

The Middle Rio Grande is a desert landscape where surface water and groundwater interaction is of particular interest due to a great degree of interaction between the two regimes. In a system that has fully appropriated its water, understanding the physical processes that govern its movement is crucial. Water managers must have a tool that is able to simulate both the physical processes of flow and management objectives in order to meet demands. While multiple models are available that handle surface water and groundwater interaction, none are able to incorporate localized physical processes and a complex institutional framework for water allocation and management.

CHAPTER 3 – MODFLOW-RIVERWARE LINK DESCRIPTION

3.1 Introduction

The general framework for coupling RiverWare and MODFLOW is described in this chapter. This chapter commences with a brief description of the modifications made to existing RiverWare and MODFLOW codes to facilitate the link (or coupling). The linked model design is presented using a simplified prototype model and the chapter concludes with a conspectus on the spatial and temporal variations between the models.

Throughout the remaining chapters, all RiverWare model objects will be denoted with bold font and all MODFLOW packages will be denoted in all caps italics.

3.2 Changes to MODFLOW and RiverWare Models Necessary To Implement the Link

3.2.1 MODFLOW

MODFLOW 2000 was selected over MODFLOW 2005 because at the beginning of this undertaking not all standard features available in MODFLOW 2000 were available in MODFLOW 2005. At that time, MODFLOW 2005 was newly released and had limited capabilities. Selecting MODFLOW 2005 would have required developers to convert existing models created in MODFLOW 2000 to the new release. Additionally, it was important to include one non-standard MODFLOW package, the Riparian Evapotranspiration (*RIP-ET*) package (Maddock and Baird, 2003), which was written into MODFLOW 2000 version 1.15. All modifications described here were made to the MODFLOW 2000 version 1.15 containing *RIP-ET* modifications.

Several MODFLOW subroutines were modified to allow for the MODFLOW RiverWare coupling. A new MODFLOW FORTRAN library was created and contains subroutines that are primarily based on MODFLOW's MAIN procedure, along with a few additional subroutines. The functionality in the new subroutines and modified existing subroutines allows RiverWare processes to: start a MODFLOW computation, advance MODFLOW by one time-step, input data from RiverWare to MODFLOW, read output data from MODFLOW to be used by RiverWare, and stop a MODFLOW computation. At this time, a few processes available in MODFLOW 2000 are not supported in the linked model including the Sensitivity (SEN) and Parameter Estimation (PES) Packages.

3.2.2 RiverWare

As stated previously, RiverWare is an object-oriented, physical process model for river basins, in which multiple methods are available to represent each process. RiverWare's Objects represent physical features of the river system such as reservoirs, river reaches, water users (consumptive use and return flow), diversions, and shallow groundwater units. Several of RiverWare's existing Objects were enhanced to accommodate the link with MODFLOW: the **Reach**, **Water User**, **Aggregate Diversion Site,** and **GroundWater objects** each contains new methods that allow an objects' data to be exchanged with MODFLOW. Essentially, data from RiverWare that is shared with MODFLOW replaces data that is input by the user in four MODFLOW packages: the General Head Boundary (*GHB*), River (*RIV*), Streamflow-Routing (*STR*), and updated Streamflow-Routing (*SFR*). The RiverWare Computational Subbasin structure was utilized for communication between the Objects MODFLOW. The role of the Computational Subbasin is described further in Section 3.3.4.

3.3 System Description with Prototype Model

A description of the linked RiverWare and MODFLOW model is presented using a prototype RiverWare-MODFLOW interaction. Plan and cross section views of the prototype are shown in Figure 3.1 and all possible data exchanges are listed in Table 3.1. Figure 3.1 contains a MODFLOW grid with several surface water features superimposed on it (bold and dashed black lines), and RiverWare objects designated as boxes. The model extends across the width of the riparian corridor and all MODFLOW grid cells shown are considered active. Each data exchange is denoted with an arrow and is numbered. A few of the data transfers shown (Numbers 8 and 9) are entirely handled within RiverWare and do not represent an exchange between RiverWare and MODFLOW and are shown for system illustration purposes.

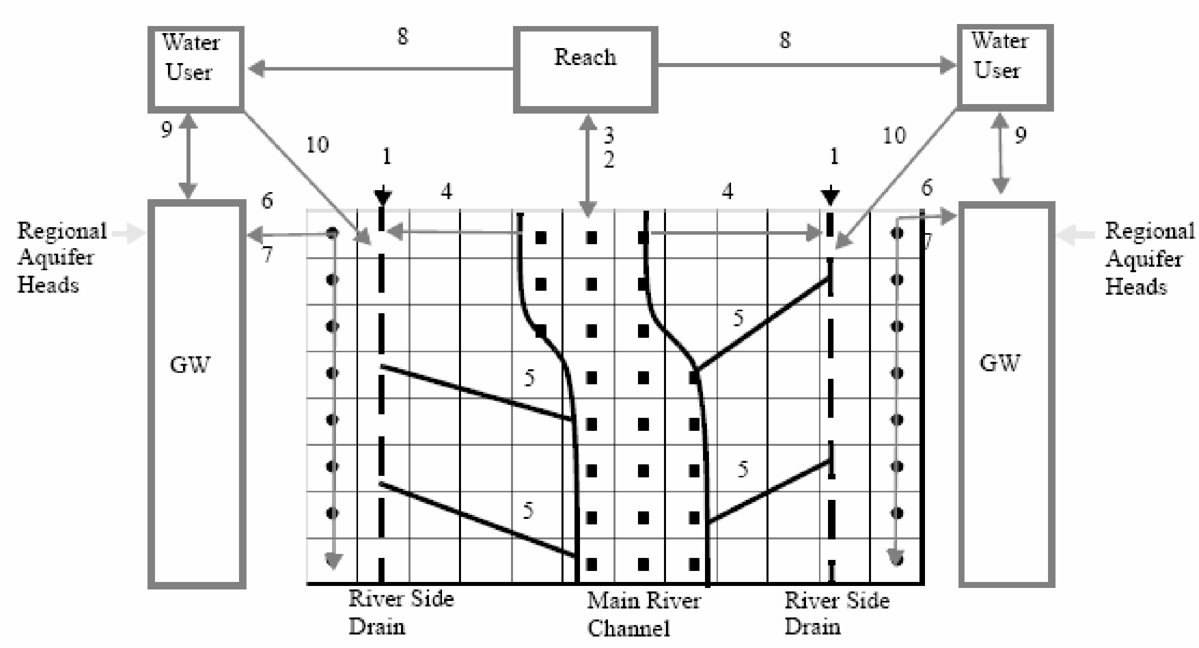
In the prototype the main river channel is included in both MODFLOW (cells with square nodes) and RiverWare (boxed **Reach** object) models. Representing the river in both RiverWare and MODFLOW affords the following options: multiple flow routing methods; flow may be subjected to management constraints; and flux between the river and aquifer may be calculated at a high resolution. Another surface water feature depicted in the prototype model is a riverside drain/canal: two riverside drains are shown (dashed black lines) one on either side of the main river channel.

The model boundaries are defined using *GHB* cells in MODFLOW (denoted with circular markers). These boundary conditions are also incorporated into RiverWare using the **GroundWater** object. In the prototype one **GroundWater (GW)** object spans all lateral boundary cells in the MODFLOW model.

Figue 3.1a) Plan and Cross Section Views of the RiverWare-MODFLOW Interaction – A plan view of a river corridor is shown below containing a main river channel (bold black lines) and two drains one on either side of the river (dashed lines). A MODFLOW grid is shown with *RIV* cells denoted with square markers and *GHB* cells with circular markers, the *STR-SFR* reaches as the dashed black lines to the right and left of the river. RiverWare Objects are designated as boxes. Each data exchange is denoted with an arrow and is numbered.

(1) Inflow into riverside drain – in MODFLOW
(2) River Stage – to MODFLOW
(3) Gain/Loss between river and aquifer – from MODFLOW
(4) Diversion from **Reach** to riverside drain – to MODFLOW
(5) Local Inflow/Return Flow from riverside drain to **Reach** – from MODFLOW
(6) **GroundWate**r Head – to MODFLOW
(7) Lateral Flux between MODFLOW Lateral Boundary cell and RW **GroundWater** object head from MODFLOW
(8) Diversion from **Reach** to **WaterUser** or **AggDiversionSite** – in RiverWare
(9) **GroundWater** Return Flow – in RiverWare
(10) Surface Water Return Flow – to MODFLOW

Regional Aquifer Heads – in MODFLOW and RiverWare are input by the user



Figue 3.1b) Plan and Cross Section Views of the RiverWare-MODFLOW Interaction - A cross section view of a river corridor is shown below containing a main river channel and two drains one on either side of the river. A MODFLOW grid is shown with *RIV* cells denoted with square markers and *GHB* cells with circular markers. The *STR* or *SFR* package is used to represent the drains these are shown as dips on either side the main river channel. RiverWare Objects are designated as boxes. Each data exchange is denoted with an arrow and is numbered.

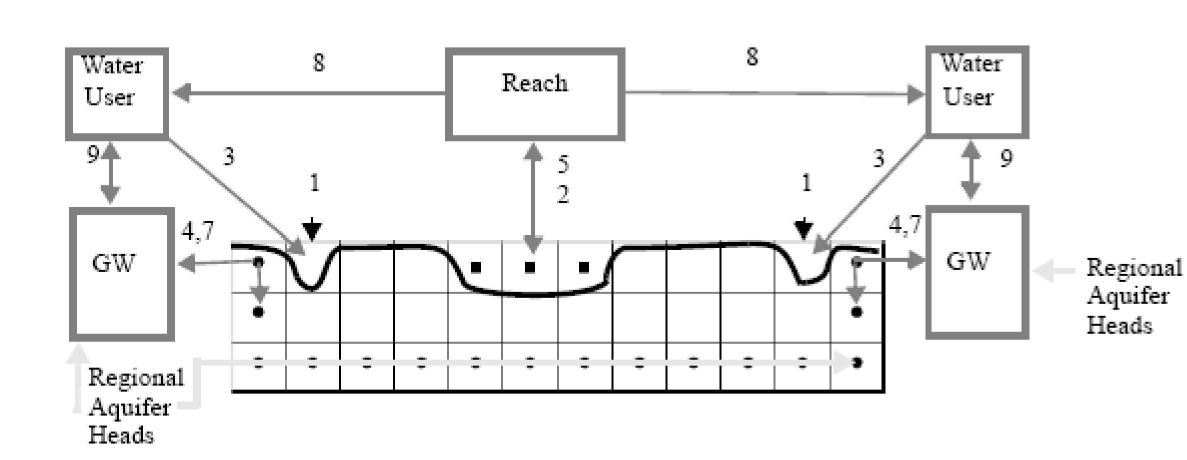


Table 3.1) Data Exchange Summary

Simulation Object	Slot	Sum, Interpolation, or Single Value	MODFLOW Identifier	From	To
Reach	Total MODFLOW GainLoss	SUM (multiple cells)	Multiple cells (Layer,Row, Column)	MODFLOW	RiverWare
Reach	Inflow Stage and Outflow Stage	Interpolation	Multiple cells (Layer,Row, Column)	RiverWare	MODFLOW
GroundWater Storage	Lateral Flux from MODFLOW	SUM (multiple cells)	Multiple cells (Layer,Row, Column)	MODFLOW	RiverWare
GroundWater Storage	Previous Elevation	Interpolation	Multiple cells (Layer,Row, Column)	RiverWare	MODFLOW
Reach	Local Inflow MODFLOW Return	Single Value	Segment #	MODFLOW	RiverWare
Reach	Diversion	Single Value	Segment #	RiverWare	MODFLOW
Water User	Surface Return Flow	Single Value	Segment #	RiverWare	MODFLOW
AggDiversion	Total Surface Return Flow	Single Value	Segment #	RiverWare	MODFLOW

3.3.1 Main River Channel

In MODFLOW the main river channel is represented using the *RIV* package and in RiverWare using a **Reach** object. The *RIV* package calculates flow into or out of a cell from an external source in proportion to the difference between the head in the cell and the river stage, as shown in the Equations 3.1a) and 3.1b) below (McDonald and Harbaugh, 1988).

If $h_{i,j,k} \rangle RBOT_n$ then $QRIV_n = CRIV_n \left(HRIV_n - h_{i,j,k} \right)$ Equation 3.1a

If $h_{i,j,k} \langle RBOT_n$ then $QRIV_n = CRIV_n \left(HRIV_n - RBOT_n \right)$ Equation 3.1b

Where:

n	is the reach number
$QRIV_n$	is the flow between the river and the aquifer, taken as positive if it is directed into the aquifer (L^3/T)
$CRIV_n$	is the hydraulic conductance of the river-aquifer interconnection (L^2/T)
$HRIV_n$	is the water level elevation (Stage) in the river (L)
$RBOT_n$	is the river bottom elevation (L)
$h_{i,j,k}$	is the head in the cell underlying the river reach (L)

And $CRIV_n = \dfrac{KLW}{M}$ Equation 3.2

Where:

K	is the riverbed conductivity
L	is the length of the riverbed
W	is the width of the riverbed
M	is the thickness of the riverbed

In RiverWare, the main river channel is represented using a **Reach** object. In the linked model, several methods for routing flow are available on the **Reach** object: no routing, time lag, variable time lag, and Muskingum Cunge. In addition to the physical process methods available in RiverWare, Rule-Based Simulation allows for policy and decision logic to be implemented on river and reservoir operations. For more information about the available routing methods and Rule Based Simulation, see RiverWare Online Help Documentation (CADSWES, 2007).

As shown in the prototype, the data exchanged between the river and the aquifer includes stage or river elevation (Figure 3.1 – Number 2) and gain/loss (Figure 3.1 - Number 3). The river stage elevation as calculated in RiverWare is transferred to MODFLOW, MODFLOW then calculates the gain/loss between the main river channel and the shallow groundwater. The purpose of connecting the *RIV* package cells with a RiverWare **Reach** object is to allow the main river channel calculations, except seepage, to be performed in RiverWare. The RiverWare **Reach** object is preferred to the MODFLOW *STR* and *SFR* packages for modeling river operations since policy and decision logic can be applied and RiverWare has more surface flow routing techniques available.

3.3.2 Riverside or Interior Drain/Canal

A riverside or interior drain or canal may be represented in MODFLOW using the *STR* or *SFR* packages. In *STR* and *SFR* packages the continuity equation is used to route piece-wise steady, uniform, constant-density stream flow (Prudic, 1989 and Prudic et al., 2004). The *STR* and *SFR* packages do not have the capability to incorporate complex surface water management operation strategies into a MODFLOW model. Drains/canals typically have few management regulations governing flow within them. Therefore, the options available in the MODFLOW *STR* and *SFR* packages provide an appropriate representation of these features and thus the drains/canals would not need to be explicitly represented in RiverWare. Additionally, drains/canals may have a strong hydraulic connection with the shallow aquifer below, and a high degree of resolution is need to accurately quantify the flux between the drain/canal and aquifer, and MODFLOW calculations are much better suited for representing features at high resolution than RiverWare. Since the drain/canal is a surface water body, an option was added to allow flow between the drain/canal explicitly represented in MODFLOW and RiverWare surface water bodies. In MODFLOW's *STR* and *SFR* Packages, stream/river/drain networks are assembled using reaches and segments. Reaches are joined together to form segments and all reaches in a segment share the same model properties. A reach can span up to one model cell, while segments can span multiple cells. Segments are numbered sequentially starting with the most upstream segment. The reaches in a segment are also numbered sequentially starting at the most upstream reach.

Four possible exchanges between a drain/canal represented in MODFLOW and a surface water body represented as a RiverWare object were developed as described below. For purposes of this discussion a MODFLOW riverside or interior drain/canal will be referred to as a drain.

1. A diversion from the main river channel to drain is possible (Figure 3.1 – Number 4 and possibly Number 1). This diversion from a RiverWare **Reach** object is assigned as inflow into a MODFLOW *STR* or *SFR* segment.
2. A return flow from a drain to the main river channel is possible (Figure 3.1 – Number 5). This return flow diverted from a MODFLOW *STR* or *SFR* segment can be specified as a local inflow into a RiverWare **Reach**.

3. A surface return flow from a **WaterUser** to a drain is possible (Figure 3.1 – Number 10). This surface return flow from a RiverWare **WaterUser** is assigned as inflow into a MODFLOW *STR* or *SFR* segment.

4. A surface return flow from multiple **WaterUsers** at once to a riverside or interior drain is possible (Figure 3.1 - Number 10). This surface return flow from a RiverWare **AggDiversion Site** is assigned as inflow into a MODFLOW *STR* or *SFR* segment.

3.3.3 Boundary Fluxes

Boundary conditions are a necessary component in a MODFLOW model. The RiverWare **GroundWater** object (GW in Figure 3) was modified to incorporate these boundary conditions into RiverWare and to manage groundwater return flows from other RiverWare **WaterUser** objects water users. Several fluxes associated with boundary conditions are illustrated in the prototype, with only the first pertaining to a data exchange between RiverWare and MODFLOW (Figure 3.1 – Number 7). The three remaining fluxes are calculated in RiverWare and accounted for in the storage equations of the **GroundWater** objects.

The first flux, which is a lateral boundary flux, is represented in MODFLOW using the *GHB* package. Similar to the *RIV* package, the *GHB* package simulates flow into or out of a cell from an external source in proportion to the difference between the head in the cell and the head assigned to an external source (McDonald and Harbaugh, 1988). The equation is shown below:

$$QB_n = CB_n\left(HB_n - h_{i,j,k}\right) \qquad \text{Equation 3.3}$$

Where:

n	is the boundary number;
QB_n	is the flow into cell i,j,k from the boundary, taken as positive if it is directed into the aquifer (L^3/T);
CB_n	is the hydraulic conductance of boundary (L^2/T);
HB_n	is the head elevation (boundary head) assigned to the external source (L);
$h_{i,j,k}$	is the head elevation in cell i,j,k (L)

In this case the external source head is an elevation transferred from RiverWare (**GroundWater** object elevation) to MODFLOW (Figure 3.1 – Number 6). Using this elevation, MODFLOW calculates the flux for each lateral boundary cell. This flux is then transferred to RiverWare (Figure 3.1 – Number 7) and used in the storage mass balance equation on the RiverWare **GroundWater** object V_{LF} in Equation 3.4 below.

$$S_{GW}(t) = S_{GW}(t-1) + V_{SW} + V_{LF} - V_{Perc} + V_{Adj} \qquad \text{Equation 3.4}$$

Where:

$S_{GW}(t)$	is the storage on the GroundWater object (L^3) at time t;
$S_{GW}(t-1)$	is the storage on the GroundWater object at the previous time-step (L^3);
V_{SW}	volume of return flow from another RiverWare object (L^3);
V_{LF}	lateral boundary flux from MODFLOW as a volume (L^3);
V_{Perc}	volume lost to deep percolation (L^3);
V_{Adj}	volume gained from adjacent GroundWater objects (L^3);

The second flux is a head-based flux calculated between linked upstream and downstream **GroundWater** objects within RiverWare. This flux is not shown in the prototype but is part of the **GroundWater** object storage equation, V_{Adj} in Equation 3.4. The equation used to calculate the flux exchanged between adjacent **GroundWater** objects is shown below:

$$Q_{Adj} = Cond \times (Elevation_{AdjGW}(t-1) - Elevation_{GW}(t-1) \qquad \text{Equation 3.5}$$

Where:

$Elevation_{GW}$	is the water table elevation in the GroundWater objects' (L)
$Elevation_{AdjGW}(t-1)$	is the adjacent GroundWater objects' water table elevation at the previous time-step (L);
$Cond$	is the conductance between the GroundWater object and the adjacent GroundWater object (L^2/T);
$S_{GW}(t-1)$	is the storage on the GroundWater object at the previous time-step (L^3);
S_y	is the specific yield of the GroundWater object;
A	is the area of the GroundWater object (L^2);

The water table elevations in the Groundwater objects are computed from:

$$Elevation_{GW} = Elevation_{GW}(t-1) + \frac{S_{GW} - S_{GW}(t-1)}{S_y A} \qquad \text{Equation 3.6}$$

Where:

$Elevation_{GW}$	is the GroundWater objects' water table elevation (L);
$Elevation_{GW}(t-1)$	is the GroundWater objects' water table elevation at the previous time-step (L);
S_{GW}	is the storage on the GroundWater object (L^3);
$S_{GW}(t-1)$	is the storage on the GroundWater object at the previous time-step (L^3);
S_y	is the specific yield of the GroundWater object;
A	is the area covered by GroundWater object (L^2);

The third flux is a head-based flux V_{Perc} between the **GroundWater** object and the deep aquifer, which depends on the head difference between them:

$$Q_{Perc} = Cond_{DeeAq} \times \left(Elevation_{GW}(t-1) - Elevation_{DeepAq}(t-1)\right) \qquad \text{Equation 3.7}$$

Where:

Q_{Perc}	is the flux between the GroundWater object and the Deep Aquifer (L^3);
$Cond_{DeepAq}$	is the Deep Aquifer Conductance (L^3);
$Elevation_{GW}(t-1)$	is the water table elevation in the GroundWater object at the previous time-step (L);
$Elevation_{DeepAq}(t-1)$	is the head elevation in the Deep Aquifer at the previous time-step (L), shown as Regional Aquifer Head in Figure 3.1;

A corresponding deep aquifer boundary should be incorporated into the base layer of the MODFLOW model using the *GHB* package. In addition to the fluxes, the RiverWare **GroundWater** object accepts return flows from other RiverWare objects, which are denoted as V_{SW} in Equation 3.4 (Figure 3.1 – Number 9)).

3.3.4 Spatial Considerations of the Linked Model

The conceptual framework of the MODFLOW and RiverWare models are very different. MODFLOW calculations are performed along a spatial grid, while RiverWare calculations occur on or between linked objects. Since the model resolutions may not directly match, some spatial interpolation/summation may be necessary for data transfer. Since the MODFLOW grid is likely to be at a finer resolution than the RiverWare objects, a mapping is needed from multiple MODFLOW cells to a single RiverWare object. Accordingly, spatial interpolation and summation between some exchanged variables is necessary. This interpolation and summation is facilitated using the RiverWare Computational Subbasin structure, in which the user is able to identify which MODFLOW model cells/segments correspond to a given RiverWare object. Additionally, the linked model framework allows for multiple MODFLOW models to be associated with a single RiverWare model. All the objects corresponding with one MODFLOW model are grouped into single Computational Subbasin. Figure 3.2 presents an example for mapping MODFLOW cells to RiverWare **Groundwater** and **Reach** objects when summation and interpolation are needed. When a RiverWare **Reach** is associated with multiple MODFLOW cells, seepage values are computed for each MODFLOW cell and summed to obtain total seepage over the **Reach** (Figure 3.2). This seepage is used in the **Reach** water balance equation in RiverWare. MODFLOW cells use river stage values with a higher resolution than RiverWare can provide and stage from the **Reach** is therefore interpolated using the computed upstream and downstream values for each MODFLOW cell, for use in seepage calculation with the *RIV* package. The summation and interpolation setup for data exchanged between a **GroundWater** object and *GHB* cells differs from the **Reach** to *RIV* cell setup. Because the **GroundWater** objects typically represent relatively large regions, elevations from the **GroundWater** objects must be interpolated for use in the lateral boundary flux calculations for *GHB* cells. Since the **GroundWater** objects track only one Elevation (associated with the midpoint of the object), interpolation is needed to represent the head variation along two adjacent **GroundWater** objects (Figure 3.2).

Figure 3.2a) Mapping of MODFLOW Cells to RiverWare **Reach** Object for Interpolation and Summation. *RIV* cells are denoted with a square marker.

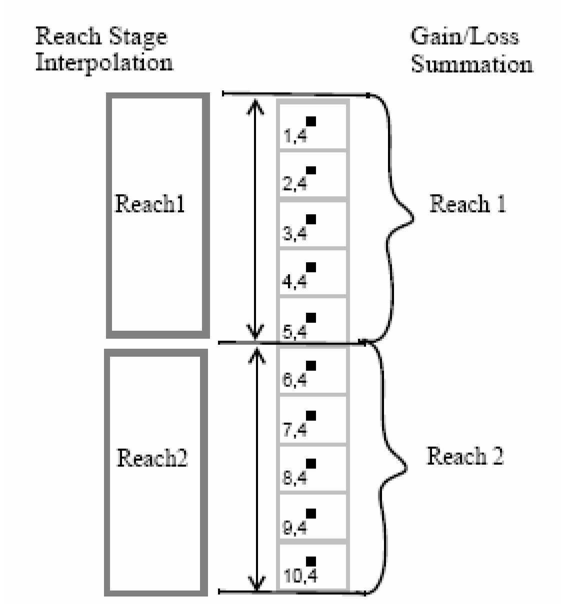
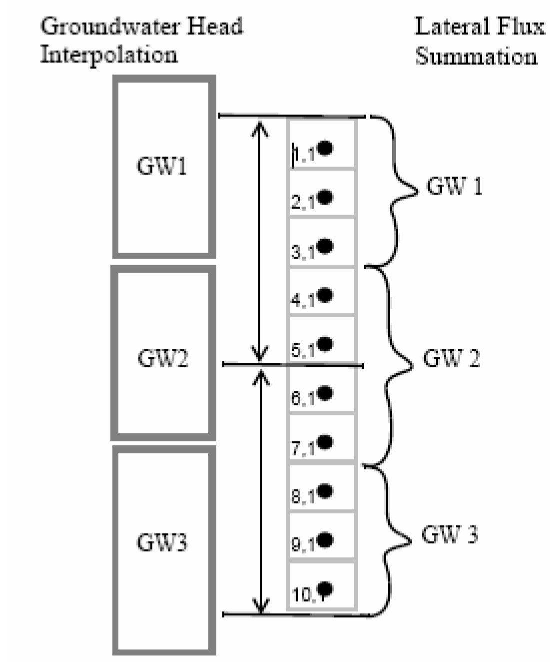


Figure 3.2b) Mapping of MODFLOW cells to RiverWare **GroundWater** object for interpolation and summation. *GHB* cells are denoted with a circular marker.



3.3.5 *Temporal Considerations For The Linked Model*

The linked model was designed for regions where groundwater storage response to changing river conditions is relatively rapid, e.g. on the order of one day. Therefore, both model components should be run using the same time-step and an interactive time stepping approach is utilized. RiverWare and MODFLOW run in parallel exchanging data after each time-step. Essentially, RiverWare and MODFLOW execute simultaneously. The sequence of operations during a typical time-step is:

1) RiverWare passes initial conditions to MODFLOW: river stage, groundwater head elevation, river diversions, water user drain return flows.

2) MODFLOW runs for one time-step and passes appropriate values to RiverWare: river/aquifer flux, flow in drain/canal, and lateral boundary flux.

3) RiverWare runs for the same time-step.

4) Advance to the next time-step. To avoid multiple iterations between the models during a single time-step, exchanged data may use parameters calculated during the previous time-step by the other model (explicit coupling).

CHAPTER 4 - CASE STUDIES

This chapter contains several model case studies each presented with details on the model setup and an analysis of the model outputs. The first case study is a demonstration that the RiverWare-MODFLOW linked model performs all computations as expected. The second case study shows that, in the absence of river management operational policy, the RiverWare-MODFLOW linked model performs similarly to a model run in MODFLOW only. The third case study applies the RiverWare-MODFLOW model to the Rio Grande near Albuquerque, New Mexico, and compares its results to two other models of the region as well as historic data. The fourth case study applies the RiverWare-MODFLOW model to the Rio Grande near Albuquerque, New Mexico to two different low flow situations: 1) gages in all three models are compared against one another in an artificial low flow situation; 2) inflow at the most upstream point in the model is determined so that a given target flow is met at the downstream end of the model. The fifth case study uses the RiverWare-MODFLOW linked model of the Middle Rio Grande to compare low, average, and high flow conditions at a future projected scenario. The last section of this chapter discusses the performance of the RiverWare-MODFLOW model.

All RiverWare model objects are denoted with bold font and all MODFLOW packages are denoted in all caps italics.

4.1 Case Study 1: Demonstration of RiverWare-MODFLOW Link Functionality

The model described below was used to test the functionality of the RiveWare-MODFLOW link. Each data exchange in the linked model design is tested to confirm that it performs as expected. This test model is similar to the prototype model described in Chapter 3. The test model represents a river corridor containing a main river channel with two drains, one on either side of main channel. Examples of movement of water between the surface water features represented in RiverWare and surface water features represented in MODFLOW are included. There are two diversions from the main river channel to the drains, two drain outflows into the main river channel, and two excess surface return flows from water users to the riverside drains represented in the model.

4.1.1 Description of Test Model

The RiverWare Model contains 6 **Reach** objects, 11 **GroundWater** objects, 2 **WaterUser** objects, and 2 **AggDiversionSite** objects (Figure 4.1). The **Reach** objects model open channel flow. The **Reach** performs several operations: it can route flow using several methods (e.g. time lag, Kinematic, and Muskingum); it can accept outflows and diversions from other objects such as diversions, gains/losses, and return flows; and it can calculate in-channel flow parameters such as stage and volume. The **GroundWater** object is a simple fill-and-spill underground body of water where the storage and outflow are calculated using a mass balance equation. Several different configurations of the **GroundWater** object are possible. In a RiverWare-MODFLOW linked model the **GroundWater** objects represent flux between MODFLOW and RiverWare along the model boundaries that represent the outer edge of the riparian zone. The **GroundWater** objects can be linked to one another (Upstream and Downstream) and the flux between objects is head driven. The **GroundWater** object can also accept inflows from surface water bodies such as irrigation groundwater return flows. The **WaterUser** object simulates the behavior of a single water user that accepts inflows from other objects. It contains a variety of methods for calculating the amount of water to be consumed by a given user, depending on needs of water consumer. It keeps track of the amount of water delivered to the object (during low flows not all requested water may not be delivered), and it contains several methods to calculate return flows (i.e. water not consumed or drained after consumption). The **AggDiversion Site** object is a collection of several **WaterUser** objects. It performs the same calculations as an individual **WaterUser** and additionally provides totals over all objects in the set and allows the user to pick how the objects will solve (lumped, sequentially, etc.).

The MODFLOW model is a rectangular grid of 300 cells, 15 rows by 20 columns, with 20 cells designated as *GHB*, 30 cells designated as *RIV*, and 18 *STR* or *SFR* segments defined (Figure 4.2). Two separate MODFLOW models were tested, one with the drains represented using the *STR* package and one with the drains represented using the *SFR* package. All other inputs in the two MODFLOW models are identical. In Figures 4.2 and 4.3 the blue cells represent *RIV* boundary conditions, the green cells represent *GHB* boundary conditions, and the pink/purple cells imply *STR* or *SFR* boundary conditions, where the purple cells indicate the beginning of a MODFLOW *STR* or *SFR* segment.

Figure 4.1) Test Model - RiverWare

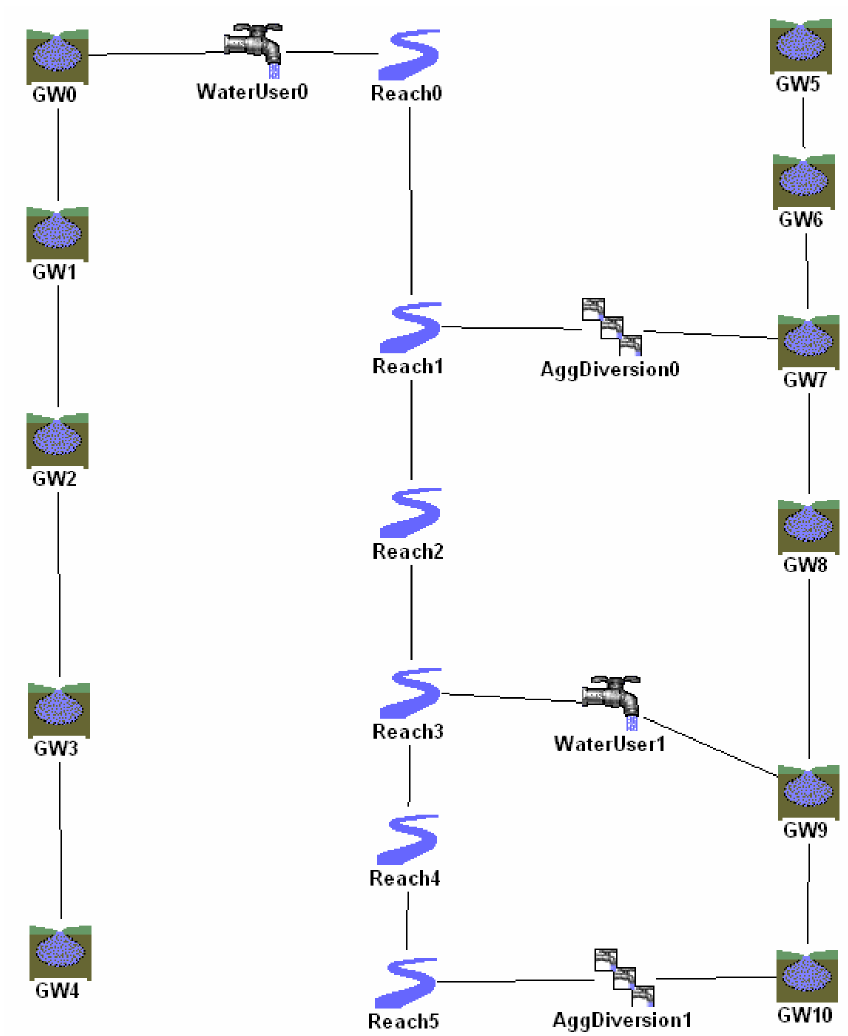
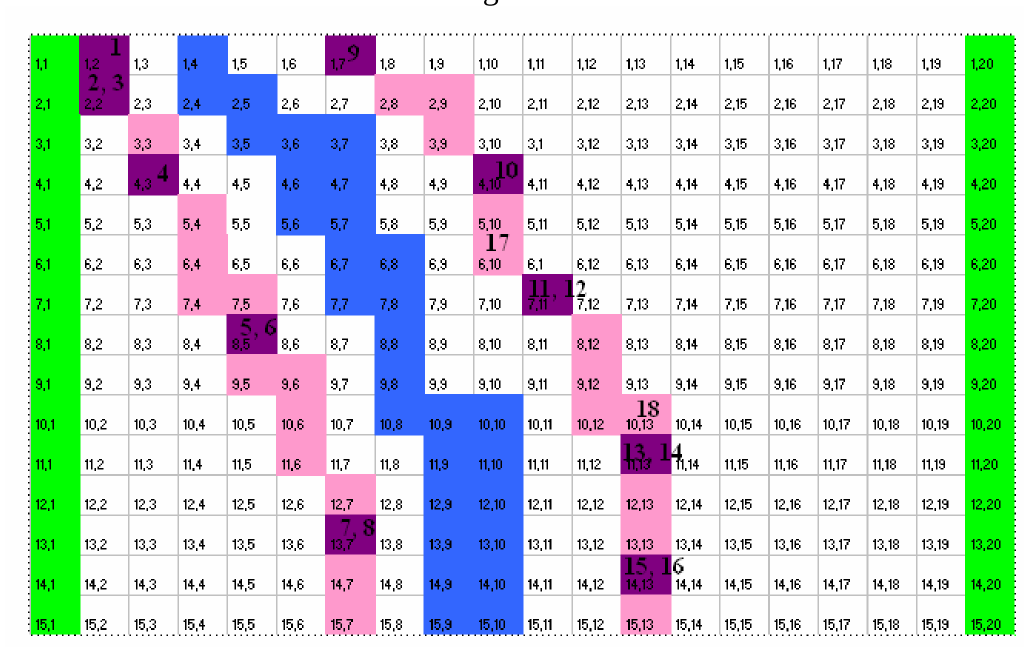


Figure 4.2) Test Model - MODFLOW Model Grid with Stream Segments Marked: *RIV* cells shown in blue, *GHB* cells are shown in green, cells which are overlain by *STR/SFR* segments are shown in pink and purple. The large bold numbers denote the *STR/SFR* Segment Number.



In Figure 4.2 the stream segment (*STR/SFR*) numbers are shown with some cells containing more than one segment. Each **Reach** object exchanges data with between four and six MODFLOW *RIV* cells and each **GroundWater** object exchanges data with between two and five MODFLOW *GHB* cells. Eight of the MODFLOW *STR/SFR* segments exchange data with RiverWare, two exchange data with **WaterUser** objects, two exchange data with **AggDiversionSite** objects, and four exchange data with **Reach** objects (Figure 4.3 and Figure 4.4).

Figure 4.3) Test Model - MODFLOW Model Grid with RiverWare Objects Marked: *RIV* cells shown in blue, *GHB* cells are shown in green, cells which are overlain by *STR/SFR* segments are shown in pink and purple. The mapping between each RiverWare object and MODFLOW cells is shown. On the *RIV* cells **Reach** objects are denoted in bold with black partitions marking the object boundaries. On the *GHB* cells **GroundWater** objects are denoted in bold with the black partitions marking the division between **GroundWater** objects for lateral flux summation and the gray partitions marking the division between **GroundWater** objects for elevation interpolation. On the *STR* cells **Reach**, **WaterUser**, and **AggergateDiversion** objects are shown in bold on the cell that exchanges flow with RiverWare.

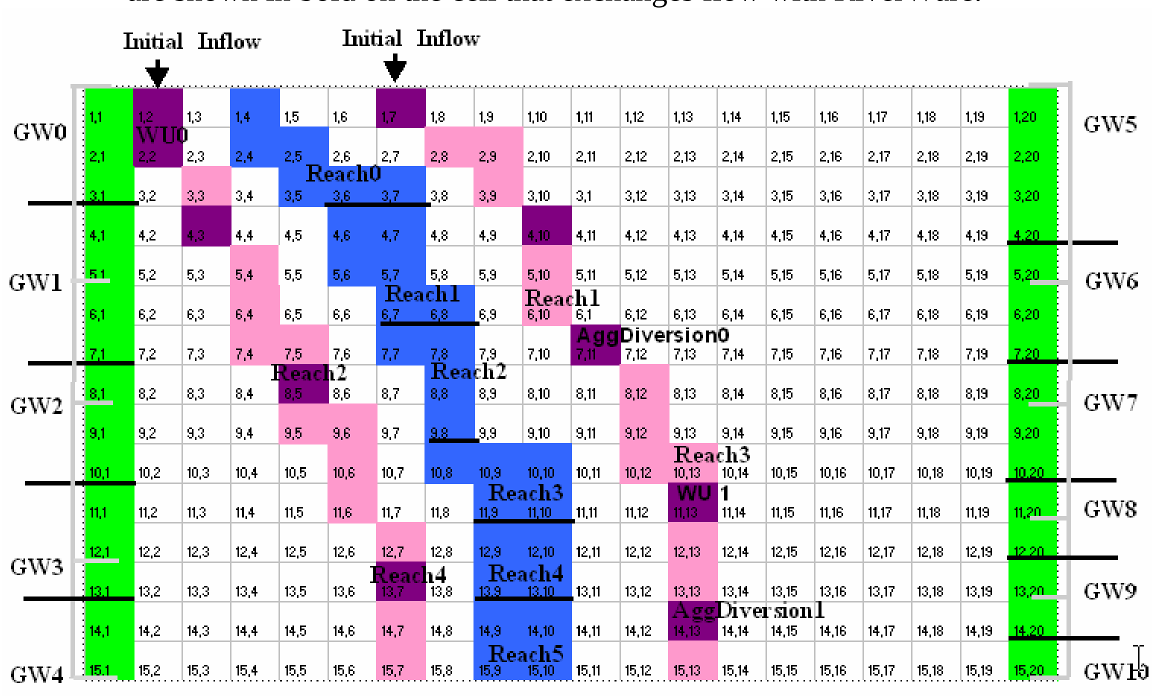
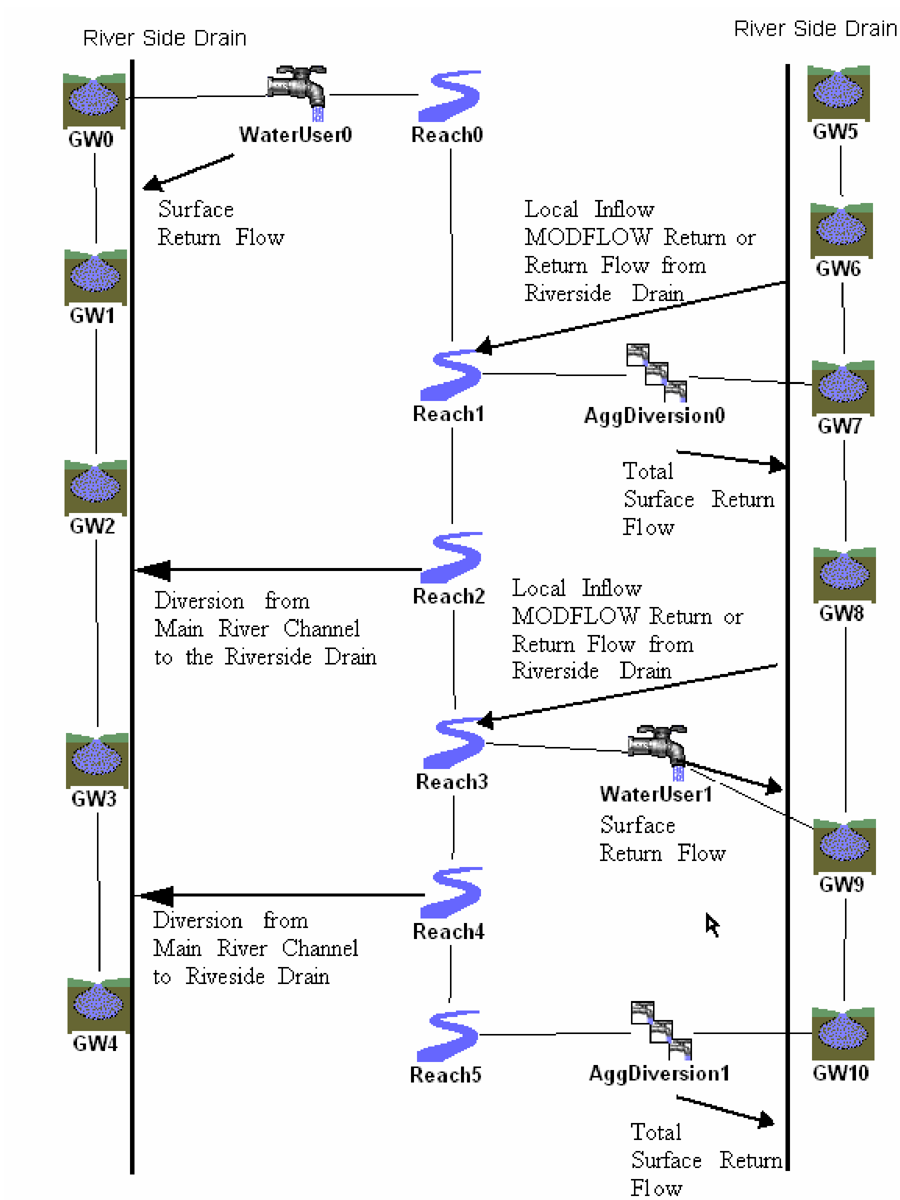


Figure 4.3 shows a schematic of how the MODFLOW model cells and segments match up with RiverWare model objects. Figure 4.4 shows a schematic of the RiverWare model with the data exchanges between surface water bodies in MODFLOW and in RiverWare marked. For each RiverWare **Reach**, the stage interpolation and gain/loss flux summation equations use the same MODFLOW cell to **Reach** mapping. Therefore, all blue cells (*RIV*) between the black dividers are marked with the matching RiverWare **Reach** name. For the **GroundWater** objects, lateral flux is summed over all cells corresponding to one **GroundWater** object,

while the head is interpolated from between two **GroundWater** objects. All green cells (*GHB*) between the black dividers are summed to obtain the lateral flux for the indicated **GroundWater** object. Table 4.2 lists the **GroundWater** object to *GHB* cell mapping for lateral flux interpolation and summation. Heads are interpolated for all green cells (*GHB*) between the gray dividers. Table 4.3 shows the MODFLOW *STR* to RiverWare object mappings. The MODFLOW segments that exchange data with RiverWare are set as either tributaries or diversions to/from the main drain segments. Each of these data exchange segments contain only one reach and are matched with one RiverWare object. All objects in the RiverWare model were grouped into one Computational Subbasin called TestSubbasin. All the data exchanged between RiverWare and MODFLOW is shown for each MODFLOW cell. The RiverWare object to cell mapping are listed by cell/segment in Tables 4.1 through 4.4.

In the MODFLOW model input files (*RIV*, *GHB* and *STR/STR*), dummy values were set for variables that receive data from RiverWare. When the data exchange occurs these dummy values are overwritten with values from RiverWare. For example, in a *RIV* cell a stage value is assigned for each stress period in the .riv input file. The actual stage value used in the calculation is overwritten with a stage transferred from RiverWare during the simulation.

Figure 4.4) Test Model – RiverWare with Drain Inflows/Outflows Marked: The riverside drain inflows/outflows exchanged between the RiverWare and MODFLOW are marked with a bold arrow and a description of the value exchanged is given.



4.1.2 Test Model Outputs

Data exchanged between the two models can be viewed on the RiverWare Computational Subbasin. The values shown on the RiverWare Computational Subbasin are for each individual MODFLOW cell/segment and should correspond to those listed in the MODFLOW output file(s) (.lst or individual output files depending on the settings selected by the user). The MODFLOW output file (.lst) is structured by time-step, and contains both inputs and outputs for the *RIV*, *GHB*, and *STR* packages. It is important to note that the inputs shown in the output file (.lst) may not reflect the actual value used in the computation. As mentioned previously, a dummy value must be entered in MODFLOW in order to initiate the MODFLOW run. This dummy value may appear as the input value in the output file since MODFLOW writes this portion of the file prior to performing the computations, and thus prior to RiverWare overwriting the value. All the outputs show in the MODFLOW output file(s) should correctly match the values shown in RiverWare.

The RiverWare and MODFLOW outputs are presented in Tables 4.1 though 4.4 for every cell/segment in the Linked Model where data exchange occurs. A percent difference between the RiverWare and MODFLOW model outputs is shown and only small rounding errors are noted between the stage, head, and drain inflow/outflow values extracted from the two models. It is easier to set RiverWare outputs to contain more digits for precision than MODFLOW outputs. Thus most of the noted discrepancies are due to lack of precision in the displayed values in the output file and not the actual values exchanged between the programs. A good illustration of this discrepancy is to compare the outputs from the *STR* and *SFR* packages; *SFR* is a newer package than *STR* and the number of significant figures included in the output file is greater. Thus the percent differences between the *SFR* output and RiverWare output are less than the percent differences between the *STR* output and the RiverWare output (Tables 4.3 and 4.4). To verify that the correct stage and head values were transferred from RiverWare and used in MODFLOW, the last column in each table shows the flux calculated using the RiverWare stage/head elevation values and the equations employed by MODFLOW. Since these calculated flux values match well with the outputs from MODFLOW, it can be assumed that the correct stage/head values were used in the model.

Table 4.1a) – Data Exchanged Between RiverWare and MODFLOW *RIV* Package. Outputs from the *RIV* Package are listed by MODFLOW cell. The percent difference between MODFLOW (Table 4.1a) and RiverWare (Table 4.1b) Outputs are shown for each time-step.

Object and Cell Identifiers				**MODFLOW Input**			**MODFLOW Output**				**MODFLOW Output**				**Percent Difference Between MODFLOW and RiverWare Outputs**			
RiverWare	MODFLOW			Dummy Input Value			Groundwater Head (m)				Seepage (Gain/Loss Flux) (m^3/day)				Seepage (Gain/Loss Flux)			
Object	Lay	Row	Col	Stage (m)	Cond (m^2/day)	Rbot (m)	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
Reach0	1	1	4	560	1.00	552.5	545.5021	545.5112	545.5322	545.5679	0.8220	0.7482	0.8666	0.7805	-0.0001	0.0000	0.0000	0.0001
Reach0	1	2	4	560	1.00	552.5	545.5014	545.5103	545.5307	545.5659	0.2880	0.2177	0.3289	0.2470	0.0000	-0.0002	-0.0001	-0.0001
Reach0	1	2	5	560	1.00	552	545.4989	545.5067	545.5258	545.5590	0.7880	0.7177	0.8289	0.7470	0.0000	-0.0001	-0.0001	0.0000
Reach0	1	3	5	560	1.00	552	545.4977	545.5051	545.5236	545.5560	-0.1020	-0.1665	-0.0674	-0.1422	0.0002	0.0001	0.0000	0.0001
Reach0	1	3	6	560	1.00	552	545.4961	545.5029	545.5206	545.5520	-0.1020	-0.1665	-0.0674	-0.1422	0.0002	0.0001	0.0000	0.0001
Reach0	1	3	7	560	1.00	552	545.4950	545.5014	545.5189	545.5497	-0.1020	-0.1665	-0.0674	-0.1422	0.0002	0.0001	0.0000	0.0001
Reach1	1	4	6	560	1.00	551	545.4948	545.5011	545.5183	545.5487	0.3980	0.4102	0.5129	0.4323	-0.0001	-0.0001	-0.0001	0.0000
Reach1	1	4	7	560	1.00	551	545.4938	545.4999	545.5169	545.5470	0.3980	0.4102	0.5129	0.4323	-0.0001	-0.0001	-0.0001	0.0000
Reach1	1	5	6	560	1.00	550	545.4930	545.4988	545.5153	545.5444	1.0350	1.0405	1.1523	1.0606	-0.0003	0.0004	-0.0002	0.0002
Reach1	1	5	7	560	1.00	550	545.4923	545.4981	545.5144	545.5436	1.0350	1.0405	1.1523	1.0606	-0.0003	0.0004	-0.0002	0.0002
Reach1	1	6	7	560	1.00	548	545.4906	545.4959	545.5115	545.5397	2.5510	2.5475	2.6715	2.5651	0.0002	0.0002	0.0001	-0.0002
Reach1	1	6	8	560	1.00	548	545.4903	545.4956	545.5117	545.5404	2.5510	2.5475	2.6715	2.5651	0.0002	0.0002	0.0001	-0.0002
Reach2	1	7	7	560	1.00	547	545.4885	545.4932	545.5082	545.5352	2.9740	2.9683	3.0963	2.9853	0.0000	-0.0001	-0.0001	0.0000
Reach2	1	7	8	560	1.00	547	545.4883	545.4932	545.5088	545.5366	2.9740	2.9683	3.0963	2.9853	0.0000	-0.0001	-0.0001	0.0000
Reach2	1	8	8	560	1.00	546	545.4858	545.4905	545.5054	545.5324	1.6940	1.6882	1.8212	1.7052	0.0000	-0.0001	0.0001	0.0000
Reach2	1	9	8	560	1.00	545	545.4833	545.4875	545.5019	545.5280	0.8427	0.8327	0.9543	0.8092	0.0000	0.0000	0.0000	0.0000
Reach3	1	10	8	560	1.00	544	545.4806	545.4845	545.4984	545.5237	-0.7686	-0.5353	-0.4122	-0.5485	0.0000	0.0000	0.0000	-0.0001
Reach3	1	10	9	560	1.00	544	545.4806	545.4850	545.5001	545.5269	-0.7686	-0.5358	-0.4139	-0.5516	-0.0001	-0.0001	0.0000	0.0000
Reach3	1	10	10	560	1.00	544	545.4807	545.4855	545.5018	545.5302	-0.7687	-0.5364	-0.4156	-0.5549	0.0000	0.0000	-0.0001	0.0000
Reach3	1	11	9	560	1.00	543.5	545.4778	545.4821	545.4968	545.5231	-2.3098	-1.7529	-1.6306	-1.7559	0.0002	0.0003	-0.0002	0.0000
Reach3	1	11	10	560	1.00	543.5	545.4779	545.4826	545.4987	545.5267	-2.3099	-1.7534	-1.6325	-1.7594	0.0001	-0.0001	0.0003	-0.0001
Reach4	1	12	9	560	1.00	542.5	545.4753	545.4794	545.4939	545.5197	-3.6154	-2.8712	-2.7556	-2.8669	-0.0001	0.0002	0.0001	0.0000
Reach4	1	12	10	560	1.00	542.5	545.4753	545.4799	545.4958	545.5234	-3.6153	-2.8717	-2.7575	-2.8706	-0.0001	-0.0001	0.0001	0.0001
Reach4	1	13	9	560	1.00	541.5	545.4732	545.4771	545.4914	545.5169	-3.8132	-3.1437	-3.0370	-3.1420	0.0000	0.0000	0.0000	0.0001
Reach4	1	13	10	560	1.00	541.5	545.4731	545.4777	545.4935	545.5209	-3.8132	-3.1443	-3.0391	-3.1460	0.0000	0.0001	0.0000	0.0000
Reach5	1	14	9	560	1.00	541	545.4716	545.4753	545.4894	545.5147	-4.5215	-4.2606	-4.1926	-4.2718	0.0000	0.0001	-0.0001	-0.0001
Reach5	1	14	10	560	1.00	541	545.4717	545.4761	545.4918	545.5191	-4.5217	-4.2614	-4.1950	-4.2762	0.0000	0.0000	-0.0001	0.0001
Reach5	1	15	9	560	1.00	540	545.4705	545.4742	545.4883	545.5135	-4.6705	-4.4032	-4.3396	-4.4158	0.0000	0.0001	-0.0001	0.0001
Reach5	1	15	10	560	1.00	540	545.4710	545.4753	545.4910	545.5182	-4.6710	-4.4042	-4.3423	-4.4205	0.0000	0.0000	0.0001	-0.0001

Table 4.1b) – Data Exchanged Between RiverWare and MODFLOW *RIV* Package. Inputs for the *RIV* package are listed by MODFLOW cell.

Object and Cell Identifiers						MODFLOW Input		MODFLOW Output				MODFLOW Output				Percent Difference Between MODFLOW and RiverWare Outputs			
RiverWare Summation Object	RiverWare Interpolation Between		MODFLOW			Dummy Input Values		Groundwater Head (m)				GHB Flux (Lateral Boundary Flux) (m^3/day)				GHB Flux (Lateral Boundary Flux)			
	Up-stream	Down-stream	Lay	Row	Col	Bhead (m)	Cond (m^3/day)	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
GW0	GW0	GW1	1	1	1	549.80	10.00	545.5167	545.5330	545.5636	545.6133	42.8325	65.8043	96.9321	141.5320	-0.0001	0.0001	0.0000	-0.0001
GW0	GW0	GW1	1	2	1	549.40	10.00	545.5152	545.5306	545.5601	545.6081	38.8482	59.0269	86.4178	125.4580	0.0000	0.0000	0.0000	-0.0003
GW0	GW0	GW1	1	3	1	549.00	10.00	545.5124	545.5266	545.5540	545.5992	34.8760	52.2675	75.9293	109.4220	-0.0001	0.0000	0.0000	-0.0001
GW1	GW0	GW1	1	4	1	548.60	10.00	545.5086	545.5210	545.5459	545.5873	30.9137	45.5224	65.4613	93.4153	-0.0001	0.0001	0.0001	0.0000
GW1	GW0	GW1	1	5	1	548.20	10.00	545.5039	545.5141	545.5358	545.5726	26.9617	38.7903	55.0127	77.4365	0.0001	0.0000	0.0000	0.0000
GW1	GW1	GW2	1	6	1	547.10	10.00	545.4979	545.5056	545.5234	545.5547	16.0203	20.9283	27.4382	35.9473	-0.0002	0.0001	0.0000	-0.0001
GW1	GW1	GW2	1	7	1	546.50	10.00	545.4916	545.4966	545.5107	545.5365	10.0835	11.3193	12.6158	13.7244	-0.0002	-0.0004	0.0000	0.0000
GW2	GW1	GW2	1	8	1	545.90	10.00	545.4847	545.4872	545.4976	545.5178	4.1526	1.7161	-2.2012	-8.4932	0.0001	0.0001	-0.0002	0.0000
GW2	GW2	GW3	1	9	1	544.40	10.00	545.4768	545.4767	545.4833	545.4982	-28.7684	-39.3410	-55.0014	-78.0938	-0.0001	0.0000	0.0000	0.0001
GW2	GW2	GW3	1	10	1	543.80	10.00	545.4718	545.4699	545.4740	545.4852	-22.7176	-32.6192	-47.2782	-68.9168	-0.0001	-0.0001	-0.0001	0.0000
GW3	GW2	GW3	1	11	1	543.20	10.00	545.4678	545.4647	545.4667	545.4752	-16.6787	-25.9132	-39.5764	-59.7682	0.0001	0.0001	0.0001	0.0000
GW3	GW2	GW3	1	12	1	542.60	10.00	545.4638	545.4594	545.4596	545.4654	-10.6377	-19.2059	-31.8748	-50.6234	-0.0004	-0.0002	0.0002	0.0001
GW3	GW3	GW4	1	13	1	541.40	10.00	545.4580	545.4520	545.4500	545.4528	-40.5798	-55.3429	-76.5402	-106.9800	0.0001	-0.0001	0.0001	-0.0001
GW4	GW3	GW4	1	14	1	541.00	10.00	545.4543	545.4471	545.4435	545.4442	-44.5426	-61.6913	-85.9698	-120.4210	-0.0001	0.0000	0.0000	0.0001
GW4	GW3	GW4	1	15	1	540.60	10.00	545.4523	545.4445	545.4399	545.4393	-48.5231	-68.0613	-95.4291	-133.9000	-0.0001	0.0000	0.0000	0.0000
GW5	GW5	GW6	1	1	20	550.90	10.00	545.5288	545.5504	545.5926	545.6582	53.7125	78.0361	112.4950	161.1970	-0.0001	0.0000	0.0003	0.0001
GW5	GW5	GW6	1	2	20	550.70	10.00	545.5275	545.5487	545.5902	545.6547	51.7248	74.4278	106.4020	151.3410	0.0000	0.0000	0.0001	0.0000
GW5	GW5	GW6	1	3	20	550.50	10.00	545.5252	545.5455	545.5858	545.6486	49.7478	70.8345	100.3280	141.5120	-0.0001	0.0000	-0.0003	0.0001
GW5	GW5	GW6	1	4	20	550.30	10.00	545.5218	545.5409	545.5797	545.6401	47.7817	67.2547	94.2723	131.7050	0.0000	0.0000	0.0000	-0.0003
GW6	GW5	GW6	1	5	20	548.80	10.00	545.5172	545.5347	545.5717	545.6291	45.8281	63.6908	88.2354	121.9240	-0.0001	0.0000	0.0000	-0.0003
GW6	GW6	GW7	1	6	20	548.80	10.00	545.5108	545.5264	545.5612	545.6148	32.8919	45.2978	61.9808	84.2827	-0.0001	0.0000	-0.0001	0.0000
GW6	GW6	GW7	1	7	20	548.00	10.00	545.5037	545.5175	545.5501	545.6002	24.9627	34.2787	46.5577	62.5358	-0.0002	0.0001	0.0000	0.0001
GW7	GW6	GW7	1	8	20	547.10	10.00	545.4960	545.5078	545.5385	545.5855	17.0405	23.2672	31.1385	40.7905	-0.0001	0.0001	-0.0001	0.0000
GW7	GW7	GW8	1	9	20	545.10	10.00	545.4873	545.4971	545.5263	545.5702	-3.8735	-6.4159	-10.9723	-18.4971	-0.0001	0.0000	-0.0003	-0.0001
GW7	GW7	GW8	1	10	20	544.50	10.00	545.4797	545.4882	545.5174	545.5603	-9.7965	-15.0776	-23.5051	-36.1329	0.0000	0.0001	0.0001	-0.0001
GW8	GW7	GW8	1	11	20	543.90	10.00	545.4725	545.4807	545.5117	545.5559	-15.7245	-23.7522	-36.0690	-53.8229	-0.0001	0.0000	-0.0001	-0.0001
GW8	GW8	GW9	1	12	20	542.20	10.00	545.4655	545.4742	545.5098	545.5587	-32.6543	-48.2378	-65.7202	-78.9914	-0.0001	0.0000	-0.0001	0.0000
GW9	GW8	GW9	1	13	20	541.80	10.00	545.4600	545.4717	545.5166	545.5738	-36.6003	-53.9249	-71.1567	-78.4127	0.0001	0.0001	0.0000	0.0000
GW9	GW8	GW9	1	14	20	540.60	10.00	545.4557	545.4742	545.5364	545.6077	-48.5572	-15.7002	85.4478	172.5220	-0.0001	-0.0003	0.0000	0.0000
GW10	GW9	GW10	1	15	20	540.40	10.00	545.4536	545.4769	545.5504	545.6306	-50.5359	9.1109	169.0770	297.2010	0.0000	0.0000	-0.0003	0.0000

Table 4.2a) – Data Exchanged Between RiverWare and MODFLOW *GHB* Package. Outputs from the *GHB* package listed by MODFLOW cell. The percent difference between MODFLOW (Table 4.2a) and RiverWare (Table 4.2b) Outputs are shown for each time-step.

Object and Cell Identifiers						MODFLOW Input		MODFLOW Output				MODFLOW Output				Percent Difference Between MODFLOW and RiverWare Outputs			
RiverWare Summation Object	RiverWare Interpolation Between		MODFLOW			Dummy Input Values		Groundwater Head (m)				GHB Flux (Lateral Boundary Flux) (m^3/day)				GHB Flux (Lateral Boundary Flux)			
	Up-stream	Down-stream	Lay	Row	Col	Bhead (m)	Cond (m^3/day)	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
GW0	GW0	GW1	1	1	1	549.80	10.00	545.5167	545.5330	545.5636	545.6133	42.8325	65.8043	96.9321	141.5320	-0.0001	0.0001	0.0000	-0.0001
GW0	GW0	GW1	1	2	1	549.40	10.00	545.5152	545.5306	545.5601	545.6081	38.8482	59.0269	86.4178	125.4580	0.0000	0.0000	0.0000	-0.0003
GW0	GW0	GW1	1	3	1	549.00	10.00	545.5124	545.5266	545.5540	545.5992	34.8760	52.2675	75.9293	109.4220	-0.0001	0.0000	0.0000	-0.0001
GW1	GW0	GW1	1	4	1	548.60	10.00	545.5086	545.5210	545.5459	545.5873	30.9137	45.5224	65.4613	93.4153	-0.0001	0.0001	0.0001	0.0000
GW1	GW0	GW1	1	5	1	548.20	10.00	545.5039	545.5141	545.5358	545.5726	26.9617	38.7903	55.0127	77.4365	0.0001	0.0000	0.0000	0.0000
GW1	GW1	GW2	1	6	1	547.10	10.00	545.4979	545.5056	545.5234	545.5547	16.0203	20.9283	27.4382	35.9473	-0.0002	0.0001	0.0000	-0.0001
GW1	GW1	GW2	1	7	1	546.50	10.00	545.4916	545.4966	545.5107	545.5365	10.0835	11.3193	12.6158	13.7244	-0.0002	-0.0004	0.0000	0.0000
GW2	GW1	GW2	1	8	1	545.90	10.00	545.4847	545.4872	545.4976	545.5178	4.1526	1.7161	-2.2012	-8.4932	0.0001	0.0001	-0.0002	0.0000
GW2	GW2	GW3	1	9	1	544.40	10.00	545.4768	545.4767	545.4833	545.4982	-28.7684	-39.3410	-55.0014	-78.0938	-0.0001	0.0000	0.0000	0.0001
GW2	GW2	GW3	1	10	1	543.80	10.00	545.4718	545.4699	545.4740	545.4852	-22.7176	-32.6192	-47.2782	-68.9168	-0.0001	-0.0001	-0.0001	0.0000
GW3	GW2	GW3	1	11	1	543.20	10.00	545.4678	545.4647	545.4667	545.4752	-16.6787	-25.9132	-39.5764	-59.7682	0.0001	0.0001	0.0001	0.0000
GW3	GW2	GW3	1	12	1	542.60	10.00	545.4638	545.4594	545.4596	545.4654	-10.6377	-19.2059	-31.8748	-50.6234	-0.0004	-0.0002	0.0002	0.0001
GW3	GW3	GW4	1	13	1	541.40	10.00	545.4580	545.4520	545.4500	545.4528	-40.5798	-55.3429	-76.5402	-106.9800	0.0001	-0.0001	0.0001	-0.0001
GW4	GW3	GW4	1	14	1	541.00	10.00	545.4543	545.4471	545.4435	545.4442	-44.5426	-61.6913	-85.9698	-120.4210	-0.0001	0.0000	0.0000	0.0001
GW4	GW3	GW4	1	15	1	540.60	10.00	545.4523	545.4445	545.4399	545.4393	-48.5231	-68.0613	-95.4291	-133.9000	-0.0001	0.0000	0.0000	0.0000
GW5	GW5	GW6	1	1	20	550.90	10.00	545.5288	545.5504	545.5926	545.6582	53.7125	78.0361	112.4950	161.1970	-0.0001	0.0000	0.0003	0.0001
GW5	GW5	GW6	1	2	20	550.70	10.00	545.5275	545.5487	545.5902	545.6547	51.7248	74.4278	106.4020	151.3410	0.0000	0.0000	0.0001	0.0000
GW5	GW5	GW6	1	3	20	550.50	10.00	545.5252	545.5455	545.5858	545.6486	49.7478	70.8345	100.3280	141.5120	-0.0001	0.0000	-0.0003	0.0001
GW5	GW5	GW6	1	4	20	550.30	10.00	545.5218	545.5409	545.5797	545.6401	47.7817	67.2547	94.2723	131.7050	0.0000	0.0000	0.0000	-0.0003
GW6	GW5	GW6	1	5	20	548.80	10.00	545.5172	545.5347	545.5717	545.6291	45.8281	63.6908	88.2354	121.9240	-0.0001	0.0000	0.0000	-0.0003
GW6	GW6	GW7	1	6	20	548.80	10.00	545.5108	545.5264	545.5612	545.6148	32.8919	45.2978	61.9808	84.2827	-0.0001	0.0000	-0.0001	0.0000
GW6	GW6	GW7	1	7	20	548.00	10.00	545.5037	545.5175	545.5501	545.6002	24.9627	34.2787	46.5577	62.5358	-0.0002	0.0001	0.0000	0.0001
GW7	GW6	GW7	1	8	20	547.10	10.00	545.4960	545.5078	545.5385	545.5855	17.0405	23.2672	31.1385	40.7905	-0.0001	0.0001	-0.0001	0.0000
GW7	GW7	GW8	1	9	20	545.10	10.00	545.4873	545.4971	545.5263	545.5702	-3.8735	-6.4159	-10.9723	-18.4971	-0.0001	0.0000	-0.0003	-0.0001
GW7	GW7	GW8	1	10	20	544.50	10.00	545.4797	545.4882	545.5174	545.5603	-9.7965	-15.0776	-23.5051	-36.1329	0.0000	0.0001	0.0001	-0.0001
GW8	GW7	GW8	1	11	20	543.90	10.00	545.4725	545.4807	545.5117	545.5559	-15.7245	-23.7522	-36.0690	-53.8229	-0.0001	0.0000	-0.0001	-0.0001
GW8	GW8	GW9	1	12	20	542.20	10.00	545.4655	545.4742	545.5098	545.5587	-32.6543	-48.2378	-65.7202	-78.9914	-0.0001	0.0000	-0.0001	0.0000
GW9	GW8	GW9	1	13	20	541.80	10.00	545.4600	545.4717	545.5166	545.5738	-36.6003	-53.9249	-71.1567	-78.4127	0.0001	0.0001	0.0000	0.0000
GW9	GW8	GW9	1	14	20	540.60	10.00	545.4557	545.4742	545.5364	545.6077	-48.5572	-15.7002	85.4478	172.5220	-0.0001	-0.0003	0.0000	0.0000
GW10	GW9	GW10	1	15	20	540.40	10.00	545.4536	545.4769	545.5504	545.6306	-50.5359	9.1109	169.0770	297.2010	0.0000	0.0000	-0.0003	0.0000

Table 4.2b) – Data Exchanged Between RiverWare and MODFLOW *GHB* Package. Inputs for the *GHB* package listed by MODFLOW cell.

Object and Cell Identifiers						RiverWare Output				RiverWare Output				Calculation to Show Correct Bhead value was used			
RiverWare Summation Object	RiverWare Interpolation Between		MODFLOW			GW Object Elevation (Replaces Dummy Bhead Value) (m)				Lateral Boundary Flux (GHB Flux) (m^3/day)				Lateral Boundary Flux or GHB Flux (m^3/day)			
	Up-stream	Down-stream	Lay	Row	Col	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
GW0	GW0	GW1	1	1	1	549.8000	552.1134	555.2568	559.7665	42.8325	65.8043	96.9321	141.5321	42.8328	65.8045	96.9324	141.5317
GW0	GW0	GW1	1	2	1	549.4000	551.4333	554.2019	558.1539	38.8482	59.0269	86.4178	125.4584	38.8480	59.0271	86.4178	125.4583
GW0	GW0	GW1	1	3	1	549.0000	550.7533	553.1470	556.5414	34.8760	52.2675	75.9293	109.4221	34.8761	52.2673	75.9295	109.4220
GW1	GW0	GW1	1	4	1	548.6000	550.0732	552.0920	554.9288	30.9137	45.5224	65.4613	93.4153	30.9139	45.5221	65.4613	93.4156
GW1	GW0	GW1	1	5	1	548.2000	549.3931	551.0371	553.3163	26.9617	38.7903	55.0127	77.4365	26.9615	38.7905	55.0126	77.4368
GW1	GW1	GW2	1	6	1	547.1000	547.5984	548.2672	549.1494	16.0203	20.9283	27.4382	35.9473	16.0208	20.9286	27.4381	35.9470
GW1	GW1	GW2	1	7	1	546.5000	546.6286	546.7723	546.9090	10.0835	11.3193	12.6158	13.7244	10.0836	11.3197	12.6159	13.7245
GW2	GW1	GW2	1	8	1	545.9000	545.6588	545.2774	544.6685	4.1526	1.7161	-2.2012	-8.4932	4.1526	1.7163	-2.2015	-8.4930
GW2	GW2	GW3	1	9	1	542.6000	541.5426	539.9832	537.6888	-28.7684	-39.3410	-55.0014	-78.0938	-28.7681	-39.3407	-55.0010	-78.0941
GW2	GW2	GW3	1	10	1	543.2000	542.2080	540.7461	538.5936	-22.7176	-32.6192	-47.2782	-68.9168	-22.7180	-32.6193	-47.2786	-68.9165
GW3	GW2	GW3	1	11	1	543.8000	542.8734	541.5091	539.4983	-16.6787	-25.9132	-39.5764	-59.7682	-16.6783	-25.9130	-39.5763	-59.7682
GW3	GW2	GW3	1	12	1	544.4000	543.5387	542.2721	540.4031	-10.6377	-19.2059	-31.8748	-50.6234	-10.6381	-19.2062	-31.8752	-50.6228
GW3	GW3	GW4	1	13	1	541.4000	539.9177	537.7960	534.7548	-40.5798	-55.3429	-76.5402	-106.9801	-40.5801	-55.3431	-76.5400	-106.9798
GW4	GW3	GW4	1	14	1	541.0000	539.2780	536.8465	533.4020	-44.5426	-61.6913	-85.9698	-120.4209	-44.5428	-61.6910	-85.9701	-120.4211
GW4	GW3	GW4	1	15	1	540.6000	538.6384	535.8971	532.0492	-48.5231	-68.0613	-95.4291	-133.9001	-48.5227	-68.0615	-95.4288	-133.9004
GW5	GW5	GW6	1	1	20	550.9000	553.3539	556.8420	561.7779	53.7125	78.0361	112.4947	161.1968	53.7125	78.0359	112.4944	161.1969
GW5	GW5	GW6	1	2	20	550.7000	552.9914	556.2303	560.7888	51.7248	74.4278	106.4019	151.3410	51.7247	74.4276	106.4019	151.3409
GW5	GW5	GW6	1	3	20	550.5000	552.6289	555.6186	559.7997	49.7478	70.8345	100.3283	141.5118	49.7479	70.8341	100.3282	141.5116
GW5	GW5	GW6	1	4	20	550.3000	552.2663	555.0069	558.8106	47.7817	67.2547	94.2723	131.7054	47.7821	67.2546	94.2724	131.7055
GW6	GW5	GW6	1	5	20	550.1000	551.9038	554.3953	557.8215	45.8281	63.6908	88.2354	121.9244	45.8285	63.6908	88.2353	121.9246
GW6	GW6	GW7	1	6	20	548.8000	550.0562	551.7592	554.0431	32.8919	45.2978	61.9808	84.2827	32.8920	45.2979	61.9807	84.2827
GW6	GW6	GW7	1	7	20	548.0000	548.9453	550.2058	551.8538	24.9627	34.2787	46.5577	62.5358	24.9628	34.2788	46.5574	62.5358
GW7	GW6	GW7	1	8	20	547.2000	547.8345	548.6523	549.6645	17.0405	23.2672	31.1385	40.7905	17.0403	23.2671	31.1383	40.7907
GW7	GW7	GW8	1	9	20	545.1000	544.8555	544.4290	543.7205	-3.8735	-6.4159	-10.9723	-18.4971	-3.8730	-6.4160	-10.9726	-18.4972
GW7	GW7	GW8	1	10	20	544.5000	543.9805	543.1669	541.9471	-9.7965	-15.0776	-23.5051	-36.1329	-9.7968	-15.0776	-23.5052	-36.1325
GW8	GW7	GW8	1	11	20	543.9000	543.1054	541.9048	540.1736	-15.7245	-23.7522	-36.0690	-53.8229	-15.7247	-23.7527	-36.0690	-53.8228
GW8	GW8	GW9	1	12	20	542.2000	540.6504	538.9378	537.6596	-32.6543	-48.2378	-65.7202	-78.9914	-32.6545	-48.2379	-65.7200	-78.9910
GW9	GW8	GW9	1	13	20	541.8000	540.0792	538.4009	537.7326	-36.6003	-53.9249	-71.1567	-78.4127	-36.6002	-53.9248	-71.1565	-78.4122
GW9	GW8	GW9	1	14	20	540.6000	543.9042	554.0811	562.8600	-48.5572	-15.7002	85.4478	172.5220	-48.5569	-15.7000	85.4477	172.5222
GW10	GW9	GW10	1	15	20	540.4000	546.3880	562.4581	575.3506	-50.5359	9.1109	169.0775	297.2011	-50.5361	9.1108	169.0770	297.2007

Table 4.3) – Data Exchanged Between RiverWare and MODFLOW *STR* Package. Outputs for the *STR* package listed by MODFLOW segment number. The percent difference between MODFLOW and RiverWare Outputs is shown at each time-step.

Object and Cell Identifiers		MODFLOW Output				RiverWare Output				Percent Difference Between MODFLOW and RiverWare			
RiverWare	MODFLOW	Flow Into Stream Reach (m^3/day)				Surface Return Flow, Diversion to Drain, River Local Inflow (m^3/day)				Surface Return Flow (Flow Into Steam Reach)			
	Segment	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
WaterUser0	2	4930	6220	4980	6470	4934	6219	4975	6468	-0.08	0.02	0.10	0.04
Reach2	5	6000	6000	5000	6000	6000	6000	5000	6000	0.00	0.00	0.00	0.00
Reach4	7	6170	6170	6170	6170	6167	6167	6167	6167	0.04	0.04	0.04	0.04
AggDiversion0	11	600	406	605	606	600	406	605	606	0.00	0.06	0.01	0.07
WaterUser1	13	0	498	498	199	0	498	498	199	0.00	0.10	0.10	0.00
AggDiversion1	15	0	5270	5000	5270	0	5273	4996	5273	0.00	-0.06	0.09	-0.06
Reach1	17	1.5	2.5	3.5	4.5	1.5	2.5	3.5	4.5	0.00	0.00	0.00	0.00
Reach3	18	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0	0.00	0.00	0.00	0.00

Table 4.4) – Data Exchanged Between RiverWare and MODFLOW *SFR* Package. Outputs for the *SFR* package listed by MODFLOW segment number. The percent difference between MODFLOW and RiverWare Outputs is shown at each time-step.

Object and Cell Identifiers		MODFLOW Output				RiverWare Output				Percent Difference Between MODFLOW and RiverWare Outputs			
RiverWare	MODFLOW	Flow Into Stream Reach (m^3/day)				Surface Return Flow, Diversion to Drain, River Local Inflow (m^3/day)				Surface Return Flow (Flow Into Steam Reach)			
	Segment	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4	t=1	t=2	t=3	t=4
WaterUser0	2	4934	6219	4975	6468	4934	6219	4975	6468	0.00	0.00	0.00	0.01
Reach2	5	6000	6000	5000	6000	6000	6000	5000	6000	0.00	0.00	0.00	0.00
Reach4	7	6167	6167	6167	6167	6167	6167	6167	6167	-0.01	-0.01	-0.01	-0.01
AggDiversion0	11	600	406	605	606	600	406	605	606	0.00	0.01	0.01	0.01
WaterUser1	13	0	498	498	199	0	498	498	199	0.00	0.00	0.00	0.00
AggDiversion1	15	0	5273	4996	5273	0	5273	4996	5273	0.00	0.00	0.01	0.00
Reach1	17	1.5	2.5	3.5	4.5	1.5	2.5	3.5	4.5	0.00	0.00	0.00	0.00
Reach3	18	1.0	2.0	3.0	4.0	1.0	2.0	3.0	4.0	0.00	0.00	0.00	0.00

4.2 Model Descriptions for Case Studies 2, 3, 4, and 5

Case Studies 2, 3, 4, and 5 include many of the same models with only slight modifications. In this section a description of each of the models and the variations between them are provided. All RiverWare model objects are denoted with bold font and all MODFLOW packages are denoted in all caps italics. The scenarios in case studies 2, 3, 4, and 5 all simulate 2-year long periods using a daily time-step in both RiverWare and MODFLOW.

4.2.1 MODFLOW Models

All the MODFLOW models described below are intended to be run while linked with RiverWare, except for the MFOnly run described in Section 4.2.1.1. The MFOnly models are MODFLOW model that were used to validate the RiverWare-MODFLOW linked model.

4.2.1.1 Cochiti to Central 1999-2000

Two MODFLOW groundwater models, Upper Albuquerque Riparian Model (S.S. Papadopulos and Associates and NMISC, 2005) (Figure 4.5) and Cochiti Riparian Model (S.S. Papadopulos and Associates and NMISC, 2007) (Figure 4.6), provided by the NMISC required minor changes to accommodate a link with RiverWare. The Cochiti MODFLOW Model covers the region from south of the Cochiti Reservoir to the Angostura Diversion Dam, and the Upper Albuquerque MODFLOW Model covers the region from Angostura Diversion Dam to Central Avenue just south of I-40. Data included in the models support a run for the years 1999-2000. Both Riparian models use 125 by 250 foot grid cells with their axis aligned lengthwise along the river. The model grids contain 122 columns by 444 rows (Cochiti) and 255 columns by 458 rows (Upper Albuquerque) of cells. As discussed in Section 1.1.7.1, the Riparian models were created using input from the Regional Groundwater model. Each riparian model contains four layers with thicknesses of roughly 20, 30, 30, and 100 feet. The actual thickness of the first layer varies with the land surface. These 4 model layers correspond to the top 3 layers in the Regional Groundwater model. (See description of Regional Groundwater model in Section 1.1.7.1). Layer 1 in the Regional Groundwater model relates to layer 1 in the Riparian models; layer 2 in the Regional Groundwater model relates to layers 2 and 3 in the Riparian models; and layer 3 in the Regional Groundwater model relates to layer 4 in the Riparian models. For a detailed description of the MODFLOW model file inputs, see the referenced documents (S.S. Papadopulos and Associates and NMISC, 2005 and 2007). The most crucial adjustments made to the MODFLOW input files were to accommodate a daily time-step. Changes to several input files were completed to account for this modification. Additional changes were necessary to the *RIV*, *STR*, and *RIP-ET* packages.

When the Upper Albuquerque and Cochiti Models are lined up end to end there is an overlap at the boundary between them. To avoid data duplication in this region when the models are linked with RiverWare, the top 19 rows in the Upper Albuquerque model were removed, so the Upper Albuquerque model grid contains 255 columns by 439 rows of cells.

Figure 4.5) Upper Albuquerque MODFLOW Model: *RIV* Cells (Blue), *GHB* Cells (Green), *STR* Cells (Pink), and Inactive Cells (Gray).

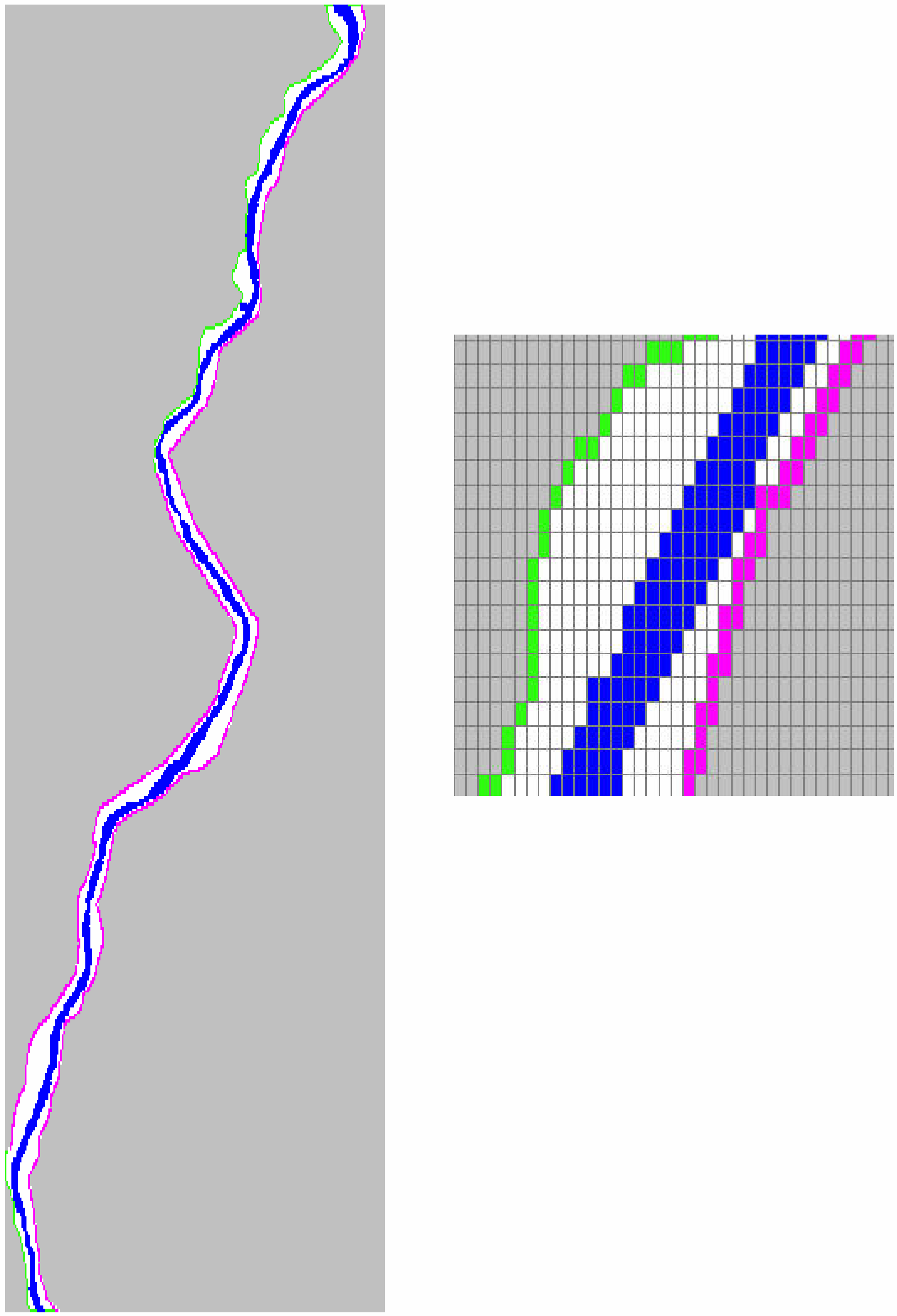
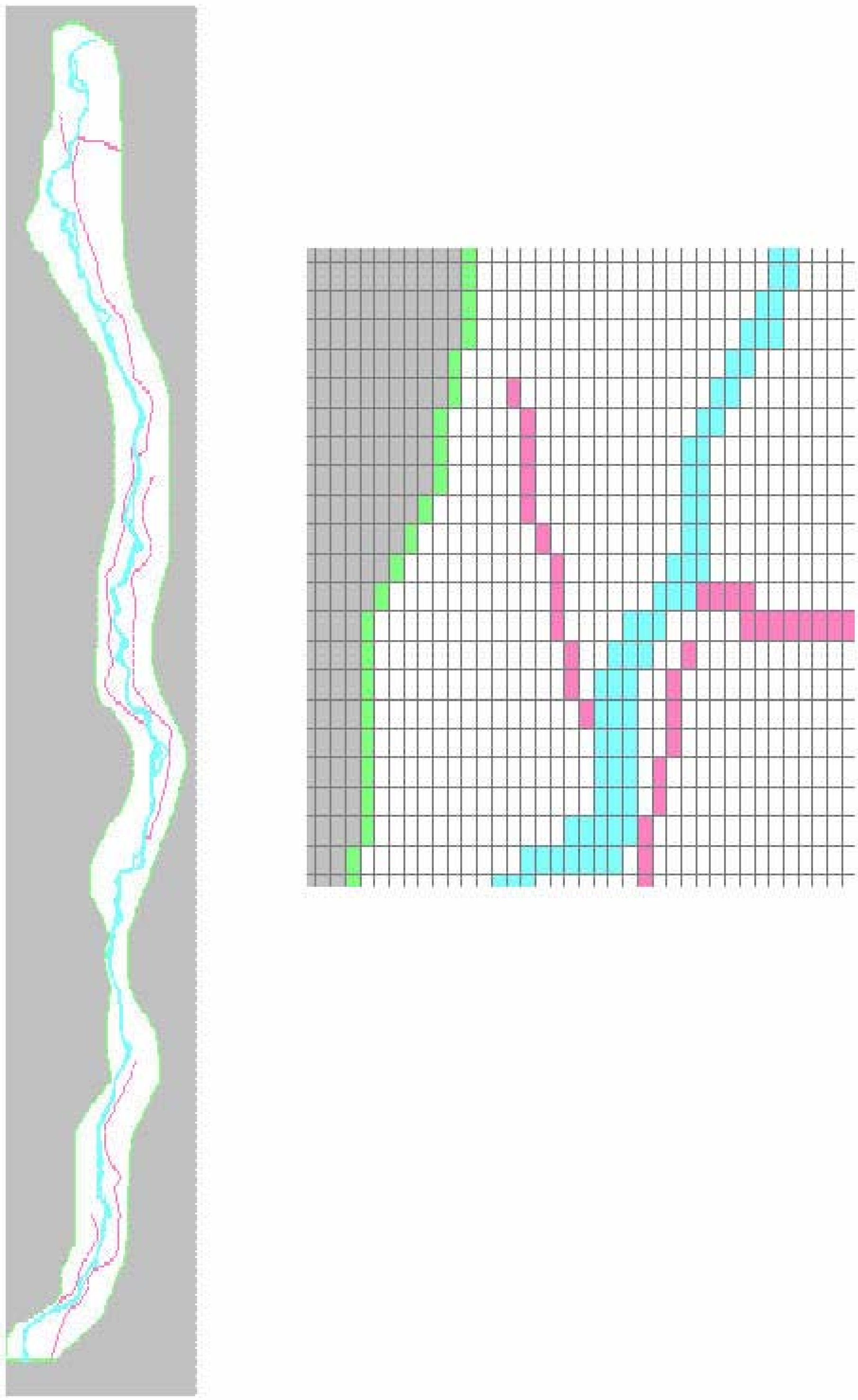


Figure 4.6) Cochiti MODFLOW Model: *RIV* Cells (Blue), *GHB* Cells (Green), *STR* Cells (Pink), and Inactive Cells (Gray).



The NMISC provided a series of *RIV* package inputs. Each input set includes a distribution of river stages and conductances developed using FLO-2D (S.S. Papadopulos and Associates and NMISC, 2005 and 2007) for a given flow rate. *RIV* input files were created for the flow rates listed below for each of the MODFLOW models: Cochiti - 100 cfs, 500 cfs, 1000cfs, 1500 cfs, 2000cfs, 2500cfs, 3000cfs, 5000cfs, 7000 cfs, and 10,000 cfs; and Upper Albuquerque -100 cfs, 500 cfs, 1000 cfs, 2000 cfs, 3000 cfs, 5000 cfs, 7000 cfs. The *RIV* input files provided were written so that each flow rate could be individually simulated. Thus in the set up provided the MODFLOW model could run with only one *RIV* flow rate at a time. For the case-study runs, all the flow rate input files were combined into one file so that transient river flows could be simulated.

Using the flow rate sets, a staircase function (Figures 4.7 and 4.8) was fitted to the gage hydrographs for the years of 1999-2000, with data obtained from the USGS website (USGS, 2007): Rio Grande below Cochiti Dam Site Number 08317400 and Rio Grande at San Felipe Site Number 08919000. A staircase function was created to mimic actual river flow, since an input file that contains a river stage and distribution for all possible river flows would be extremely cumbersome and time consuming to produce. A daily time-step was used in the case study runs, for which each stress period (time-step) was set in the *RIV* input file using the flow rate shown in the staircase function hydrograph. Since the Upper Albuquerque MODFLOW model is downstream from the Cochiti MODFLOW model, after an initial run, a new input hydrograph (Figure 4.9) was created using the middle **Reach** inflow data, SanFelipeToCentralSeepage3 (from the Linked Model). The *RIV* package inputs and stress periods were adjusted based on the new hydrograph and both the Linked Model and the MFOnly models were rerun using the new data. In addition to the input files provided by the NMISC, linear interpolation was used to create a few additional input sets from the existing sets (e.g. 1,000 cfs and 2,000 cfs sets were used to create a 1,500 cfs input set for Upper Albuquerque). Additional sets created include 300 cfs for both Cochiti and Upper Albuquerque and 1,500 cfs for Upper Albuquerque.

Figure 4.7) Rio Grande Below Cochiti Gage Daily Flow Hydrograph 1999-2000. Daily USGS flow for Site Number 08317400 is shown in blue. The staircase function fitted for MODFLOW *RIV* input file is shown in pink. Yellow data markers indicate dates for which head difference color contour plots were created for the Linked model versus the MODFLOW only model comparison.

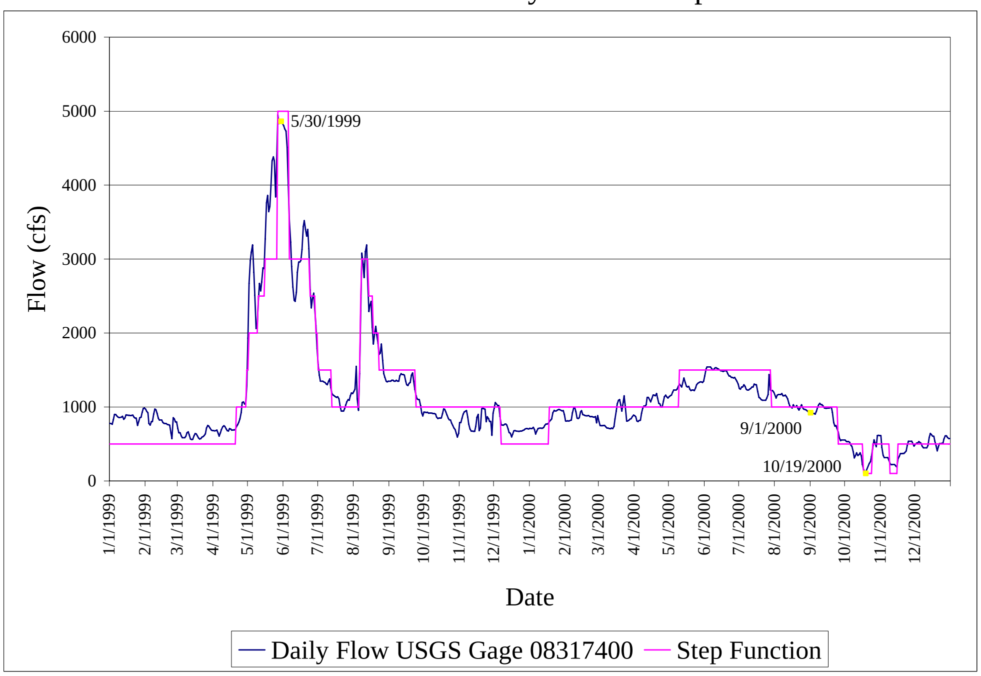


Figure 4.8) Rio Grande at San Felipe Gage Daily Flow Hydrograph 1999-2000. Daily USGS flow for Site Number 08919000 is shown in green. The initial staircase function fitted for MODFLOW *RIV* input file is shown in pink.

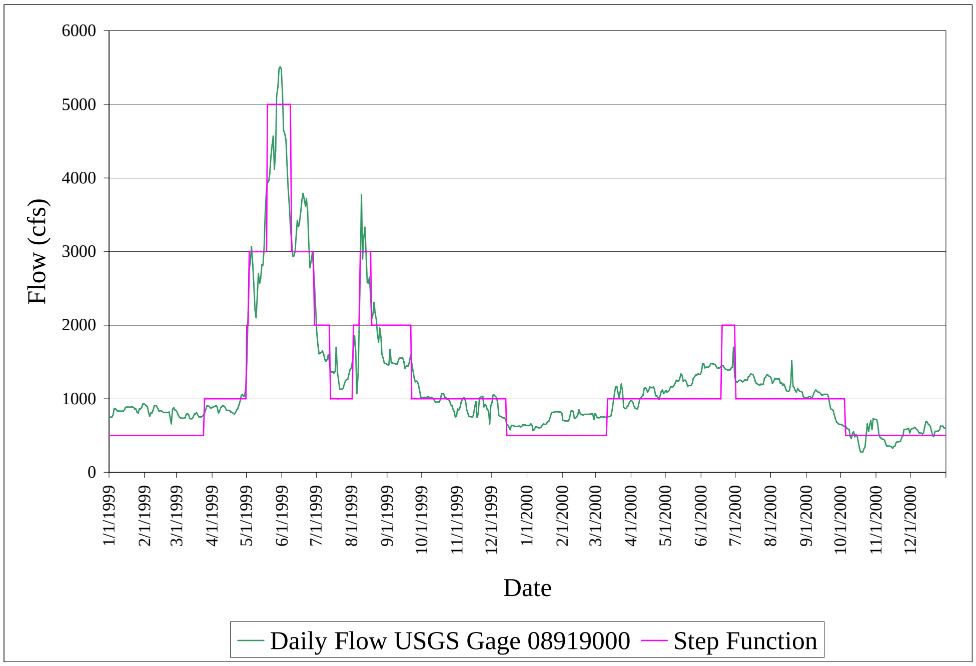
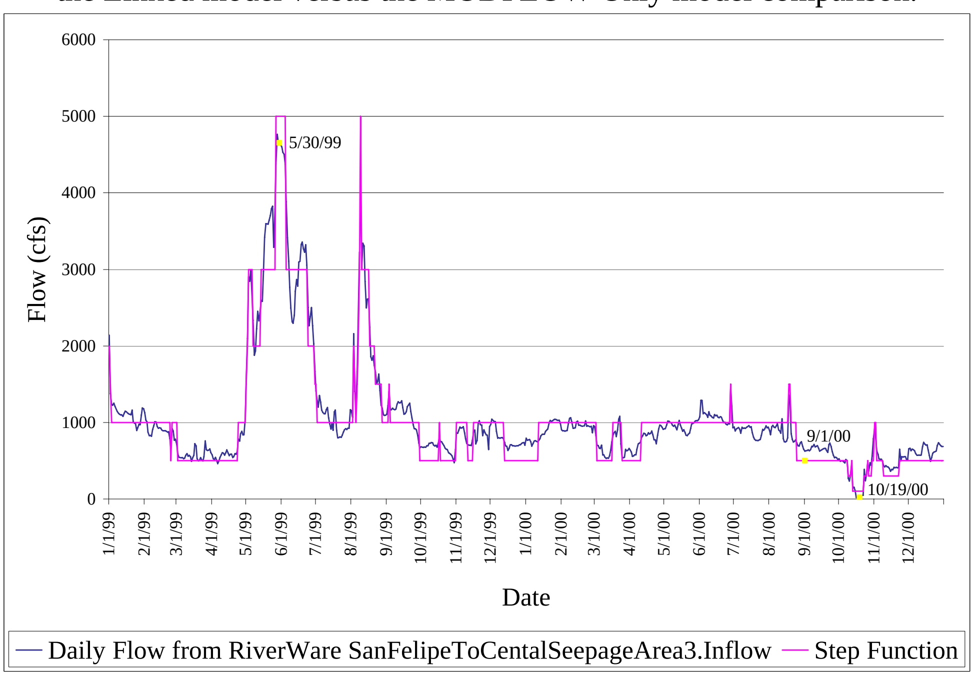


Figure 4.9) Rio Grande at San Felipe Gage Daily Flow Hydrograph 1999-2000 from RW-MF Linked model. Daily flow output from the middle **Reach** object in the Lower portion of the Cochiti to Central Linked Model is shown in blue. The final staircase function fitted for MODFLOW *RIV* input file is shown in pink. Yellow data markers indicate dates for which head difference color contour plots were created for the Linked model versus the MODFLOW Only model comparison.



The *GHB* package and *RIP-ET* package inputs provided by the NMISC were created for the year 1999. The data sets provided for the *RIP-ET* package prescribe variable monthly evapotranspiration rates. As with the *RIV* input files, an individual *RIP-ET* data set was provided for each month and is set up so that only one *RIP-ET* monthly input can be simulated during a single model run. For the case study runs, all the monthly data sets were combined into one *RIP-ET* input file so that ET changes during each month of the year could be simulated in a single model run. A daily time-step was used in the case study runs; each stress period (time-step) was set to match with the appropriate month based on the day of the year. Since input sets provided by the NMISC were only for the year 1999, the *RIP-ET* input and *GHB* input for 1999 was repeated using the same sequence in the year 2000.

Additional MODFLOW input packages/files in use but not discussed above include: basic (*BAS*), discretization (*DIS*), output control (*OC*), preconditioned conjugate-gradient (*PCG*), recharge (*RCH*), layer property flow (*LPF*), multiplier file, and zone file. For a description of each package and a list of the necessary inputs the reader is referred to the MODFLOW user documentation (Harbaugh et al., 2000; and McDonald and Harbaugh, 1988). Changes were made to the *DIS* and *RCH* files to accommodate a daily time-step and to the *OC* file to produce desired outputs. No changes were made to the remaining files for the 1999-2000 case study runs.

For the Upper Albuquerque region, the S.S. Papadopulos and Associates and NMISC model as described in the 2005 report uses *RIV* cells to define the riverside drains. In the version of the model provided by the NMISC, the riverside drains representation had been updated and currently uses *STR* cells. The drains in the

Cochiti model were initially developed using *STR* cells and the model provided by the NMISC does not vary from the S.S. Papadopulos and Associates and NMISC, 2007 report description. Minor modifications were made to the *STR* cells, such as renumbering of segments and reaches, to allow for the link with RiverWare.

While the MODFLOW models are run at a daily time-step, it should be noted that much of the required input data changes on a monthly/seasonal timescale. For example, the data inputs for the *RIP-ET* package change monthly therefore, the same ET data is used for every day in within the month.

For the MFOnly Cochiti to Central 1999-2000 model runs, all package inputs are the same as those described above except for the *STR* package. Modifications were made to the *STR* package to incorporate irrigation return flows to the drains represented in MODFLOW. The amount of irrigation water returned to the drains is significant enough to warrant their inclusion in the MFOnly run. These return flows as calculated in the RiverWare portion of the RW-MF Linked model (see description in Section 4.2.2.4) were incorporated into the daily input for the *STR* package in the MFOnly run. These return flows were set in segments 3 and 9 of the Cochiti MODFLOW model (see Table 4.5 for matching RiverWare objects).

4.2.1.2 Cochiti to Central 1976-1977

The 1999-2000 Upper Albuquerque and Cochiti MODFLOW models described above were modified for a two year low flow conditions run, 1976-1977. For the *RIV* package, using the flow rate sets discussed in the previous section, a staircase function (Figures 4.10 and 4.11) was fitted to each of the USGS gage hydrographs (08317400 and 08919000) for the years of 1976 and 1977. Each stress period (time-step) was set in the *RIV* input file using the flow rate shown in the staircase function hydrographs. For the *GHB* package, new inputs for the boundary head in each cell in layer 4 and for cells in layers 1, 2, and 3 (that do not communicate with RiverWare) were created. Heads from the Regional Groundwater model (see description of model in Section 1.1.7.1) produced by stress period 17 - time-step 6 (this stress period and time-step corresponds to simulated heads for the end of December 1975) were extracted. These heads were interpolated using inverse distance weighting. The same interpolated heads were also used to create the initial head input for all four model layers. The initial heads are specified in the *BAS* package; thus this file was modified to use the new heads corresponding to a start date of January 1, 1976. *GHB* inputs did not need to be updated for the cells that exchange data with RiverWare, since these are set by RiverWare (see Section 4.2.2.4). For the *RIP-ET* package, the stress period input for February was modified to match correctly with a leap year in 1976. The convergence criteria in the *PCG* package were made less stringent to allow the model to run to completion. Midway through the RW-MF Linked model initial run, the MODFLOW solution failed to converge and thus the run could not complete. To correct this issue the number of iterations allowed and the maximum acceptable head change for convergence were increased in the *PCG* package. No changes were made to *DIS, STR, OC, RCH, LPF*, multiplier file, and zone file.

Figure 4.10) Rio Grande Below Cochiti Gage Daily Flow Hydrograph 1976-1977. Daily USGS flow for Site Number 08317400 is shown in blue. The staircase function fitted for MODFLOW *RIV* input file is shown in pink.

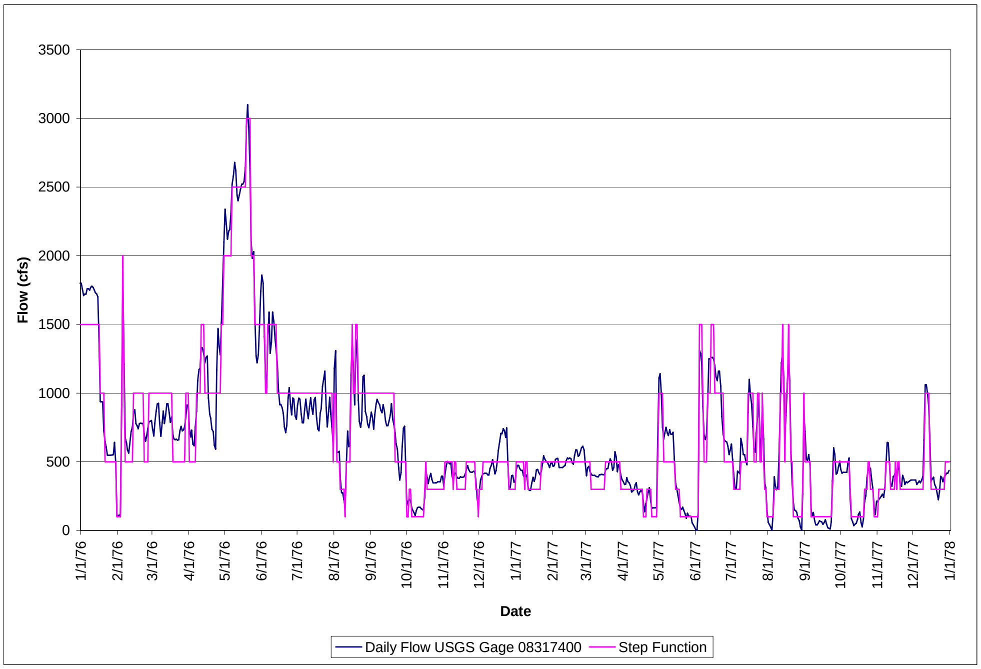
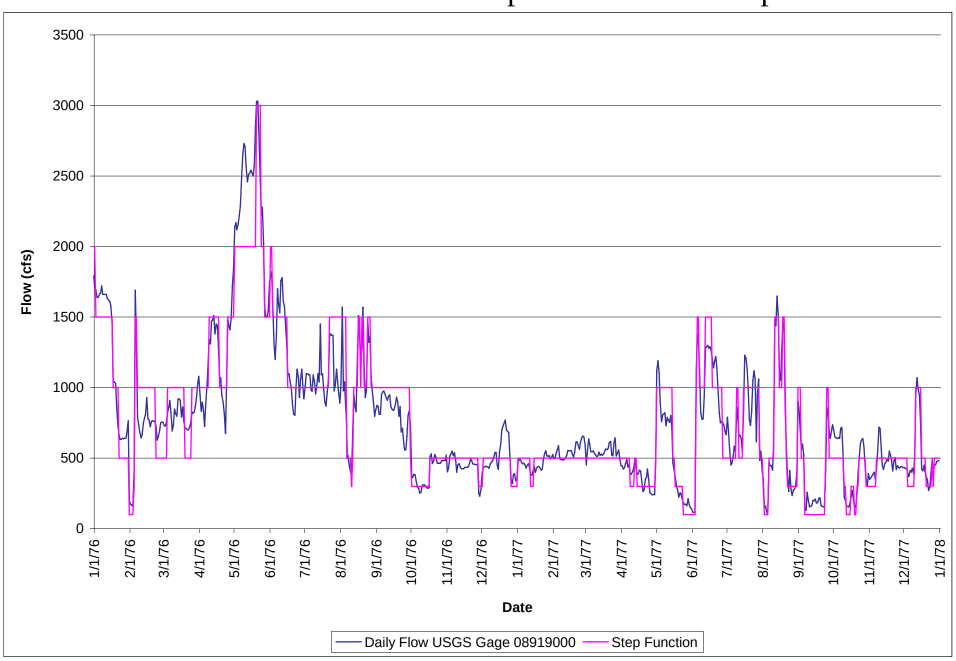


Figure 4.11) Rio Grande at San Felipe Gage Daily Flow Hydrograph 1976-1977. Daily USGS flow for Site Number 08919000 is shown in blue. The staircase function fitted for MODFLOW *RIV* input file is shown in pink.



4.2.1.3 Cochiti to Central 2040-2041

The 1999-2000 Upper Albuquerque and Cochiti MODFLOW models described above were modified to accommodate three future projections for the years of 2040-2041. The future groundwater conditions are based on a simulation-optimization study performed using the Regional Groundwater Model with future projections from 2006-2040 (Bexfield et al., 2004). For case study 5, three different scenarios were run for the years 2040 to 2041, whereby, the future projection model was subjected to three different river flow conditions: low, average, and high (river flow conditions were created from historic gage flow data of the region).

For this case study it was only necessary to create one new *RIV* package input file for 1984-1985 (Figures 4.12 and 4.13). As done previously, a staircase function was fitted to each of the USGS gage hydrographs (08317400 and 08919000) for the years of 1984-1985 (historic high flow conditions). For the two remaining scenarios, the *RIV* input files created for the 1999-2000 model (historic average flow conditions) and 1976-1977 model (historic low flow conditions) were used. For the *GHB* package, new inputs for the boundary head in each cell in layer 4 and for cells in layers 1, 2, and 3 that do not communicate with RiverWare were created. Future simulated heads in the Regional Groundwater model for December 2039 were extracted (Bexfield et al., 2004). In the Regional Groundwater model simulation-optimization study, five different approaches for minimizing groundwater impacts in the year 2040 were specified and a model simulation was created for each approach. Overall, when comparing the Regional Model 2040 simulated heads to those in 2000, all five simulations produced greater heads (ranging from a 5 foot to more than 60 foot increase) near the city of Albuquerque and lower head in the vicinity of Rio Rancho (ranging from a 5 foot to 50 foot decline). Heads were extracted from all five simulations and were interpolated using inverse distance weighting. In the vicinity of the Riparian models (Cochiti and Upper Albuquerque), no significant differences were noted between the simulated heads for the five future projections. The heads simulated by objective 1 were used to create the initial head inputs for all 4 model layers and the *GHB* package as described above. The initial heads are specified in the *BAS* package, thus it was modified to use the new heads corresponding to starting the model run on January 1, 2040. The convergence criteria in the *PCG* package were made less stringent to allow the model to run to completion, similar to the description in Section 4.2.1.2 midway through the initial RW-MF Linked Future Run using the 1984-1985 hydrograph, the MODFLOW solution failed to converge and the same procedure was followed to correct this issue. No changes were made to *RIP*, *DIS*, *STR*, *OC*, R*CH*, *LPF*, multiplier file, and zone file beyond those made for the 1999-2000 MODFLOW model setup.

Figure 4.12) Rio Grande Below Cochiti Gage Daily Flow Hydrograph 1984-1985. Daily USGS flow for Site Number 08317400 is shown in blue. The staircase function fitted for MODFLOW *RIV* input file is shown in pink.

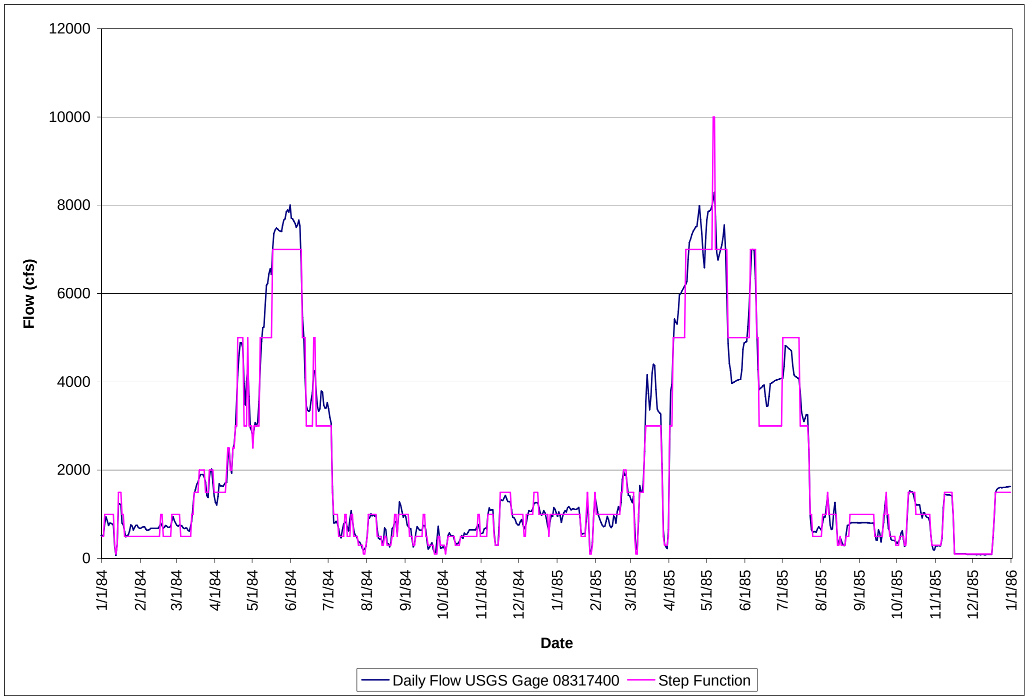
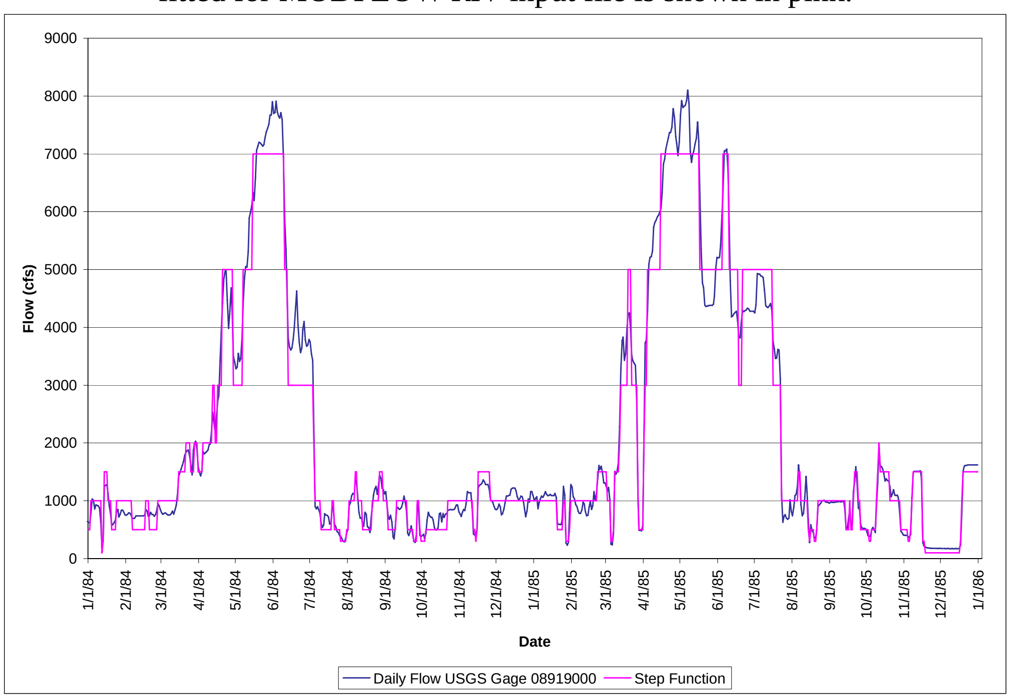


Figure 4.13) Rio Grande at San Felipe Gage Daily Flow Hydrograph 1984-1985. Daily USGS flow for Site Number 08919000 is shown in blue. The staircase function fitted for MODFLOW *RIV* input file is shown in pink.



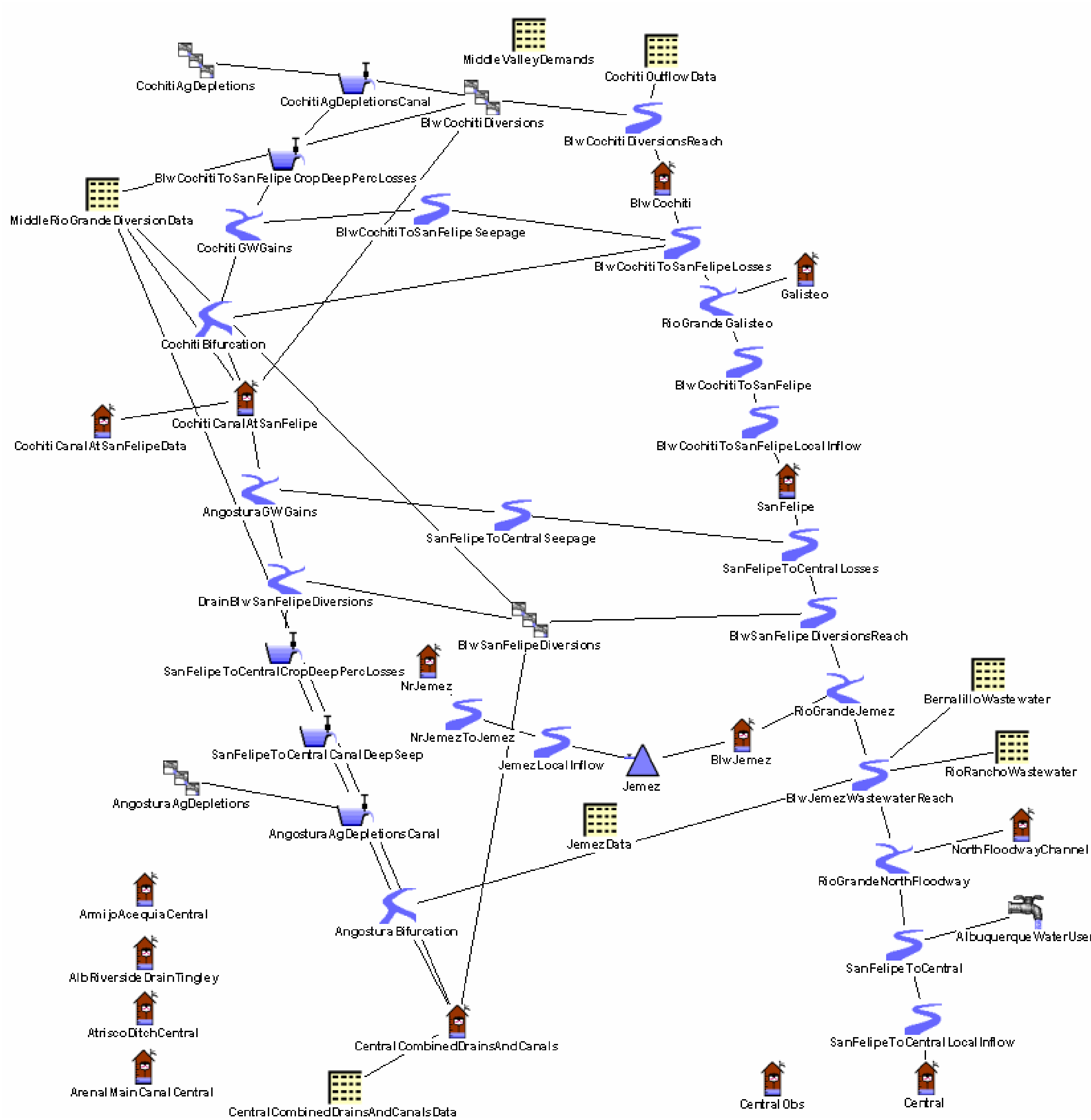
4.2.2 RiverWare Models

4.2.2.1 URGWOM Planning Model - Cochiti to Central 1999-2000

The USACE provided a truncated version of the URGWOM Planning Model which covers the region from Cochiti to Central Avenue and contains input for the years 1999-2000 (Figure 4.14). The model representation for this region is complex - it contains riverside drains, canals, acequias, laterals, turnouts, and return-flow wasteways on both the east and west sides of the river. Data inputs in the model include: river-channel evaporation loss; river-channel leakage; river routing; Middle Rio Grande Conservancy District (MRGCD) diversions; canal and riverside drain flows; municipal, wastewater return flows; MRGCD agricultural evapotranspiration loss (consumptive use); bosque or riparian evapotranspiration loss; tributary inflow; canal seepage; irrigated-acreage deep percolation; and crop, riparian and other land-use acreages (USACE, 2002). In Figure 4.14 two distinct parallel object chains are visible: the main stem of the Rio Grande is represented in the chain on the right, while river diversions to irrigation canals are represented in the chain on the left. The description provided here will focus only on aspects of the model that are needed for comparison with the RW-MF Linked models; therefore, not all features present in the model are discussed.

Along the main stem of the Rio Grande, losses from the river are calculated in two **Reaches:** BlwCochitiToSanFelipeLosses and BlwSanFelipeToCentralLosses (Figure 4.14). The method used to calculate these losses, Seepage and Riparian Consumptive Use Loss, was created specifically for the URGWOM and is based on a regression equation provided by Dave Wilkins and Carole Thomas of the USGS. This equation uses **Reach** inflow and several time varying coefficients supplied by the user to compute leakage (CADSWES, 2007). The system used to calculate the leakage coefficients was specifically calibrated to match historical data and since it is tied directly to historical gage flows, future projections using this data have been poor. An example of seepage movement within the model is documented by USACE (2002). In their example, seepage, which is the river leakage less riparian consumptive use, is passed out of the BlwCochitiToSanFelipeLosses **Reach** through the BlwCochitiToSanFelipeSeepage **Reach** to the CochitiGWGains **Reach** where it is combined with irrigation groundwater losses and canal flow. These combined losses are then compared to historic flow in the CochitiCanalAtSanFelipe **Gage.** The CochitiBifurcation object is used to make an adjustment, either positive or negative, to correct flow in the drain (if flow is too great, water is returned to the river, and if flow is too low, water is extracted from the river).

Figure 4.14) URGWOM Planning Model Cochiti to Central



4.2.2.2 URGWOM Planning Model - Cochiti to Elephant Butte 1975-1999

The USACE provided a truncated version of the URGWOM Planning Model which covers the region from Cochiti to Elephant Butte and contains input for the years 1975-1999. The region in this model from Cochiti to Central is exactly the same as the URGWOM Planning 1999-2000 except that it contains data inputs for the years 1975-1999.

4.2.2.3 URGWOM Planning GW Objects Model - Cochiti to Central 1999-2000 and 1976-1977

The USGS provided the URGWOM Planning GW Objects model which covers the region from Cochiti to Central and contains input for the years 1999-2000 (Figure 4.15). No published documentation is available for this model. This model is essentially an updated higher resolution version of the URGWOM Planning model, including **GroundWater** objects representing the shallow aquifer. Here this model is discussed in terms of its differences from the URGWOM Planning model. One can see in Figure 4.15 that the configuration of the irrigation canal diversions is different. The diversions have been split into two sections, East and West, and the setup for returning canal flow to the main stem of the river from these diversions is also different. Along each canal, the method used to calculate irrigation requests in the AgDepletion objects is different (e.g. the CochitiAgDepletions object in the URGWOM Planning model uses a different Diversion and Depletion Request Method to calculate irrigation requests than the CochitiWestSideAgDepletionsCanal object in the URGWOM Planning GW Objects model). A different method is also used to calculate canal deep seepage (e.g. CochitiAgDepletionsCanal in URGWOM Planning versus CochitiToSanFelipeWestSideCanalDeepSeep in URGWOM Planning GW Objects). In the URGWOM Planning model, the calculated canal seepage is a sink where water leaves the model. In the URGWOM Planning GW Objects model, canal seepage is linked to one of the multiple **GroundWater** objects that have been added to the model. In this model the **GroundWater** objects represent the shallow aquifer in the riparian corridor. Gains/losses from the main stem of the Rio Grande to the aquifer are also handled differently. In the URGWOM Planning model, losses from each of the Cochiti and Upper Albuquerque reaches are calculated using one **Reach** object (e.g. BlwCochitiToSanFelipeLosses) while three **Reaches** (e.g. BlwCochitiToSanFelipeSeepageArea1, CochitiToSandFelipeSeepageArea2 and SanFelipeToCentralSeepageArea1) are used in the URGWOM Planning GW Objects model. The methods used to calculate **Reach** gain/losses to the aquifer are different. The method used in the URGWOM Planning model to calculate seepage (river losses) is a regression equation (see description in the previous section). The method used to calculate gain/losses in the URGWOM Planning GW Objects model is a head based flux method which uses the head from a **GroundWater** object and the stage from a **Reach** object. Several drains that provide inflow to the main stem of the river have also been added to the URGWOM Planning GW Objects model (e.g. PenaBlancaRiversideDrain and LowerWestsideSantoDomingoDrain). These drains are not present in the URGWOM Planning model, nor are the irrigation return flows that are passed into them (e.g. CochitiToSanFelipeEastSideSWReturn).

The USGS also provided a second copy of the URGWOM Planning GW Objects model with data for the years 1976 and 1977. The objects and methods used in this model are identical to that of the 1999-2000 model, except that the inputs match the years 1976-1977. The inflow provided on the CochitiOutflowData (CochitiDam) object was modified to match with the inflows extracted from the URGWOM Planning Model Cochiti to Elephant Butte 1975-1999. A slight variation between these two models inflows for 1976-1977 was noted, and the URGWOM Planning models inflow data was selected, since it provided a better match to historic flow at the Below Cochiti Gage.

Figure 4.15a) – Upper Portion of the URGWOM Planning GW Objects Model Cochiti to Central

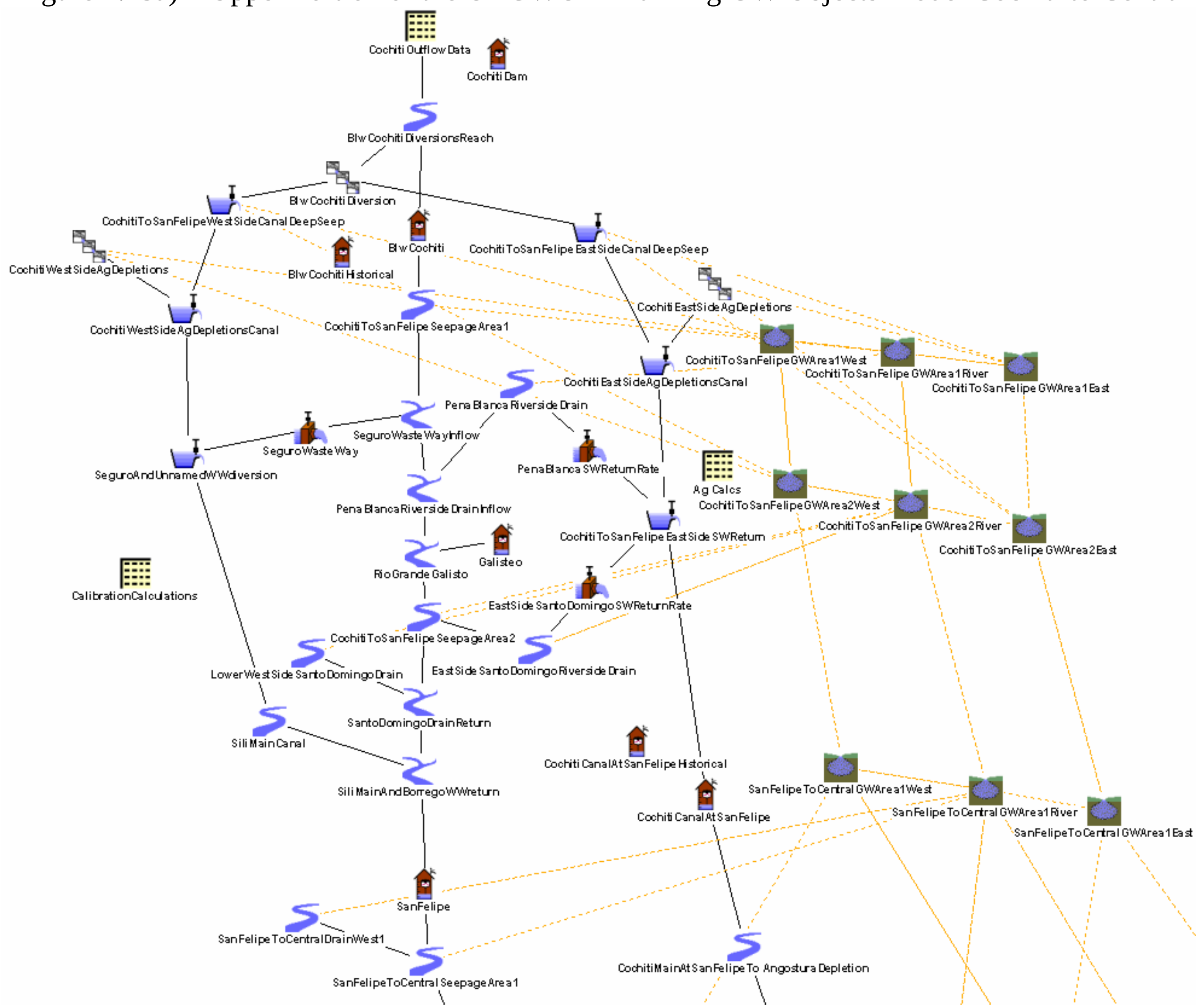
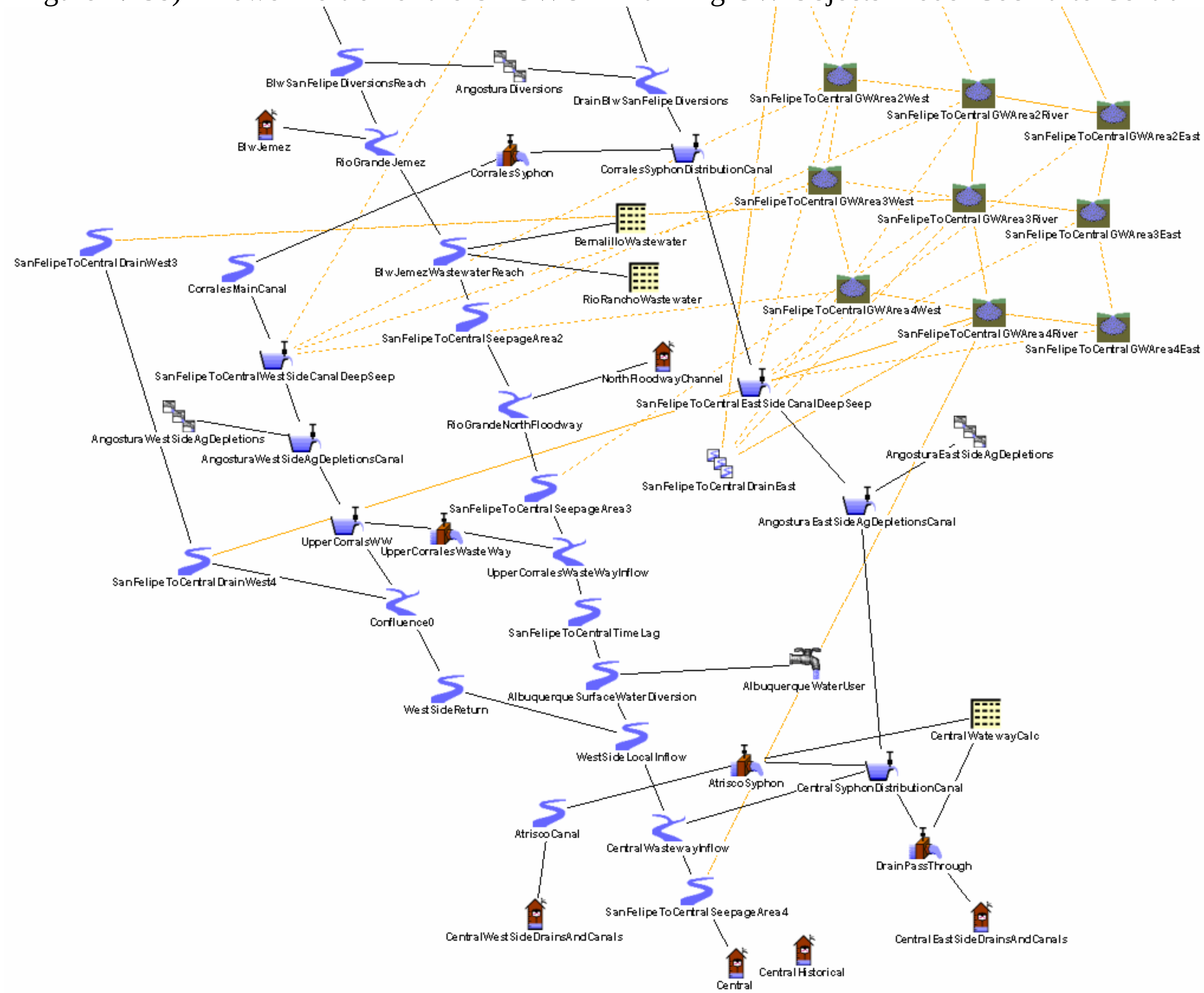


Figure 4.15b) – Lower Portion of the URGWOM Planning GW Objects Model Cochiti to Central



4.2.2.4 RiverWare portion of the RW-MF Linked Model - Cochiti to Central 1999-2000, 1976-1977, and 2040-2041

The RiverWare model linked with MODFLOW (RW-MF Linked Model 1999-2000) is a modified version of the URGWOM Planning GW Objects model 1999-2000 (Figure 4.16). Figure 4.16 shows the model split into two regions, Upper and Lower. The Upper region corresponds to the same area as the Cochiti MODFLOW model and the Lower region corresponds to the same area as the Upper Albuquerque MODFLOW model. The groundwater solution type method selected on the **GroundWater** objects in the RW-MF Linked model was changed to Link to MODFLOW GW. In the RW-MF Linked model the **GroundWater** objects represent model boundary conditions just outside the riparian corridor, whereas in the URGWOM Planning GW Objects model, they represent the entire riparian zone shallow groundwater aquifer. Accordingly, some of the **GroundWater** area inputs were adjusted, and the middle section of groundwater objects (e.g. SanFelipeToCentralGWArea1River in Figure 4.15a) was deleted. In the RW-MF Linked model gain/losses from the main stem of the Rio Grande are calculated in MODFLOW, thus the method used to calculate river gain/loss to the aquifer on each of the **Reach** objects (e.g. SanFelipeToCentralSeepageArea1) was changed. The drains such as PenaBlancaRiversideDrain are fully represented in the MODFLOW portion of the RW-MF Linked model except at the confluence with the main stem of the Rio Grande. Therefore, the irrigation surface water return flows to the drains are passed to MODFLOW using two new **Reach** objects

(PenaBlancaRiversideDrainReturnsToMODFLOW and EastSideSantoDomingoRiversideDrainReturnsToMODFLOW).

Two Computational Subbasins were added to the RiverWare model to accommodate the link with MODFLOW and the appropriate methods were selected on each. All cells in the *RIV* package that are classified as in-channel were mapped to the RiverWare **Reach** objects listed in Table 4.5. In the *RIV* package files provided by the USGS, higher flow rates contain cells for both in-channel and over-bank flow conditions. Linear interpolation was used to create the upstream and downstream weights set in the Reach Stage and Gain/Loss Map. The weights were calculated based on the height of the river bottom (in each cell) from the upstream and downstream stages corresponding to 0 cfs flow. The stage values corresponding to 0 cfs flow provided by the USGS, are for in-channel flow conditions only and do not apply to overbank flow conditions. Therefore, the cells classified as overbank were not set to exchange data with RiverWare.

On the Computational Subbasin all cells in layers 1, 2, and 3 in the *GHB* package were mapped to the **GroundWater** objects as listed in Table 4.5, except the cells bounding the northern and southern ends of the river corridor. Linear interpolation was used to create the upstream and downstream weights set in the GroundWater Elevation Upstream Map and GroundWater Elevation Downstream Map. The value of each weight was determined using linear interpolation, for which the weight assigned to a given cells was based on the distance of the cell from the boundary of the region corresponding to the upstream and downstream groundwater objects.

Figure 4.16a) Upper Portion of the RW-MF Linked Model Cochiti to Central

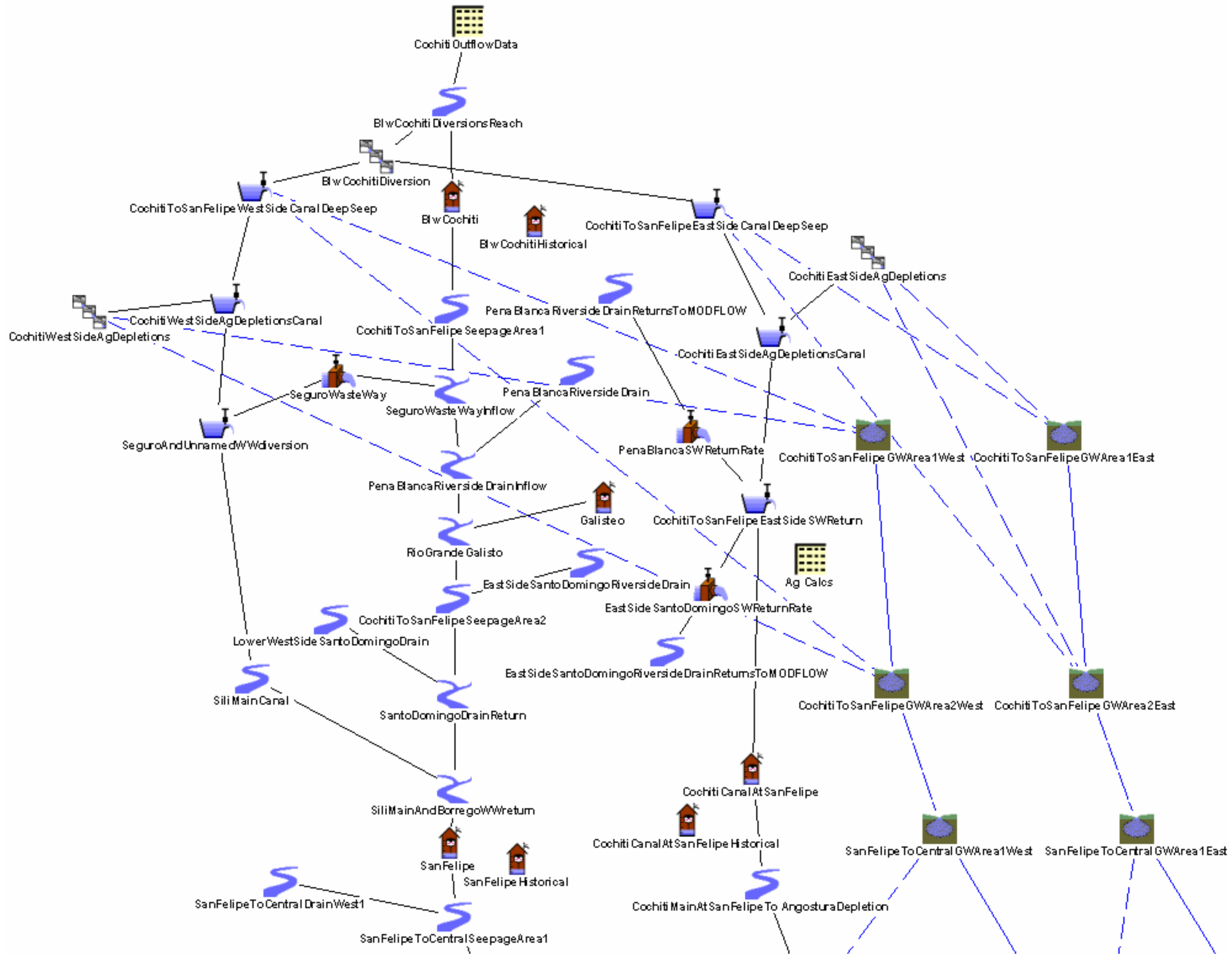


Figure 4.16b) Lower portion of the RW-MF Linked Model Cochiti to Central

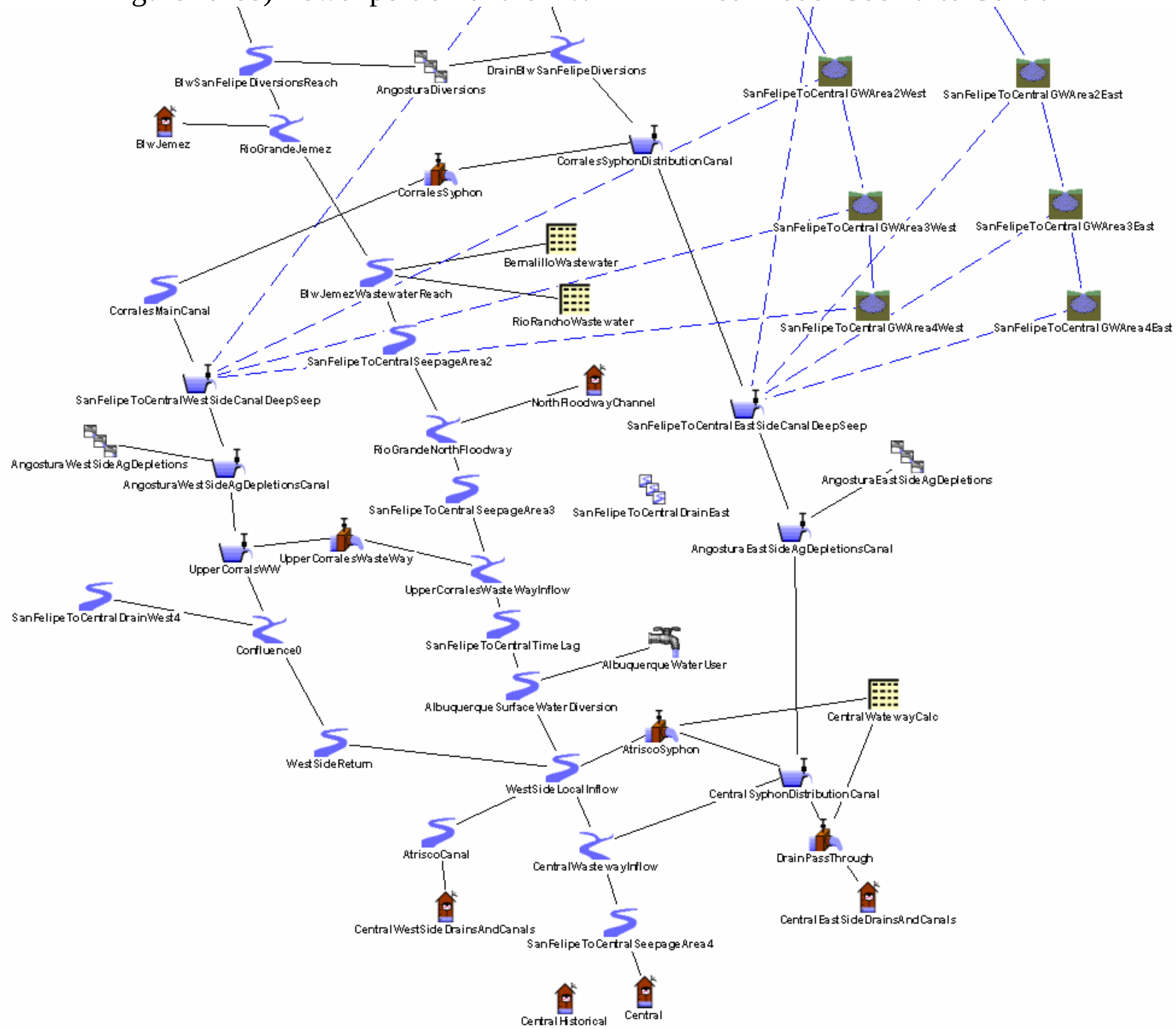


Table 4.5) RiverWare Object to MODFLOW Cell/Segment Mapping for the Cochiti to Central Case Study RiverWare Models

Local Inflow/MODFLOW Return Flow Mapping		Flow to Segement		
Object Name	**Model**	**Segment #**		
PenaBlancaRiversideDrain	Cochiti Model	5		
LowerWestSideSantoDomingoDrain	Cochiti Model	7		
EastSideSantoDomingoRiversideDrain	Cochiti Model	11		
SanFelipeToCentralDrainWest1	Cochiti Model	14		
PenaBlancaRiversideDrainRetunsToMODFLOW	Cochiti Model	3		
EastSideSantoDomingoRiversideDrainRetunsToMODFLOW	Cochiti Model	9		
SanFelipeToCentralDrainEast:Reach 4	UpperAlbuquerque Model	6		
SanFelipeToCentralDrainWest4	UpperAlbuquerque Model	8		
Reach Objects to RIV Cell Mapping		**MODFLOW Gain/Loss Summation and Interpolation**		
Reach Object Name	**Model**	**Rows**		
CochitiToSanFelipeSeepageArea1	Cochiti Model	12-168		
CochitiToSanFelipeSeepageArea2	Cochiti Model	169-299		
SanFelipeToCentralSeepageArea1	Cochiti Model	300-433		
SanFelipeToCentralSeepageArea2	UpperAlbuquerque Model	1-146		
SanFelipeToCentralSeepageArea3	UpperAlbuquerque Model	145-284		
SanFelipeToCentralSeepageArea4	UpperAlbuquerque Model	285-439		
GW Object to GHB Cell Mapping		**Lateral Flux Summation**	**Upstream Object Interpolation**	**Downstream Object Interpolation**
GroundWater Object Name	**Model**	**Rows**	**Rows**	**Rows**
CochitiToSanFelipeGWArea1West	Cochiti Model	7-167	7-233	
CochitiToSanFelipeGWArea1East	Cochiti Model	14-168	14-234	
CochitiToSanFelipeGWArea2West	Cochiti Model	168-299	234-366	7-233
CochitiToSanFelipeGWArea2East	Cochiti Model	169-300	235-366	14-234
SanFelipeToCentralGWArea1West	Cochiti Model	300-433	367-433	234-366
SanFelipeToCentralGWArea1East	Cochiti Model	301-433	367-433	235-366
SanFelipeToCentralGWArea2West	Cochiti Model			367-433
SanFelipeToCentralGWArea2East	Cochiti Model			367-433
SanFelipeToCentralGWArea1West	UpperAlbuquerque Model		1-63	
SanFelipeToCentralGWArea1East	UpperAlbuquerque Model		1-63	
SanFelipeToCentralGWArea2West	UpperAlbuquerque Model	1-145	64-214	1-63
SanFelipeToCentralGWArea2East	UpperAlbuquerque Model	1-146	64-216	1-63
SanFelipeToCentralGWArea3West	UpperAlbuquerque Model	146-283	215-439	64-214
SanFelipeToCentralGWArea3East	UpperAlbuquerque Model	147-285	217-439	64-216
SanFelipeToCentralGWArea4West	UpperAlbuquerque Model	284-439		215-439
SanFelipeToCentralGWArea4East	UpperAlbuquerque Model	286-439		217-439

For the RW-MF Linked Model 1976-1977 all the inputs in the RiverWare model correspond to data for the years 1976-1977; otherwise the setup of the model is exactly the same as the RW-MF Linked model. The 1976-1977 data provided by the USGS pertain only to inputs regarding surface flows and not to input on the **GroundWater** objects. Initial values for elevation and storage on the **GroundWater** objects were set to match with data extracted from the Regional Groundwater Model (see Section 1.1.7.1). The mean elevation for the *GHB* cells corresponding to each **GroundWate**r object was calculated using the heads extracted from layer 1 of the

Regional Groundwater Model. In the URGWOM Planning GW Objects model the initial elevation and storage values set on the **GroundWater** objects were used as calibration parameters by the USGS and were adjusted. Therefore, the mean values calculated for the 1976-1977 were adjusted by the same percentage difference as those in the URGWOM Planning GW Objects model. The new initial storage values were set using the elevation change equation from the SolveGWMBgivenPreviousElevations Dispatch Method as used by RiverWare (CADSWES, 2007). The elevation and storage from the URGWOM Planning GW Objects Model 1999-2000, and the new initial elevation were used as inputs in the equation.

For the RW-MF Linked Model 2040-2041, all inputs are based on the 1999-2000 model except for the inflow hydrograph for the main stem of the river and the initial storage and elevation set on the **GroundWater** objects. The same procedure was used to obtain the initial elevation and storage for the **GroundWater** objects in the 2040-2041 simulation as was described in the 1976-1977 discussion in the paragraph above, except that Regional Groundwater model outputs from the 2006-2040 future projection were used in place of the 1976-1977 Regional Groundwater model.

4.3 Case Study 2: Comparison of MFOnly Models 1999-2000 with Linked RiverWare-MODFLOW Model 1999-2000

The intent of this model comparison was to show that a run using a RiverWare-MODFLOW Linked Model, without operational policies (e.g. logic that determines reservoir releases or diversions), produces output similar to a model run in

MFOnly. The RW-MF Linked model example model uses the RW-MF Linked 1999-2000 RiverWare model linked with the Cochiti and Upper Albuquerque 1999-2000 MODFLOW models. For comparison, the same two MODFLOW models were executed independently of RiverWare with a slight modification as noted in Section 4.2.1.1. Throughout this Section, the RiverWare-MODFLOW Linked Model will be referred to as the RW-MF Linked model and the MODFLOW models when run individually will be referred to as the MFOnly models.

4.3.1 Results

Results from the MFOnly model runs for the UpperAlbuquerque 1999-2000 and Cochiti 1999-2000 models are compared to results from the RW-MF Linked 1999-2000 model run. This discussion is broken into parts: each subsection below details the differences in simulated output between a single relevant MODFLOW package using a MFOnly model run versus the RW-MF Linked model run.
Figures 4.17 through 4.22 show the output versus time for the lateral boundary flux (Figures 4.17 and 4.18), gain/loss between the river and aquifer (Figures 4.19 through 4.21), and local inflow/MODFLOW return flows (Figure 4.22) (for a description of these quantities the reader is directed to Chapter 3). For the RW-MF Linked model, output values for each RiverWare object that contain exchanged fluxes are compared with the MFOnly outputs. To compare the MFOnly outputs with the RW-MF Linked model outputs, the individual cell outputs from the MFOnly run were summed over the corresponding RW-MF Linked model object boundaries. Thus, this discussion is focused on the differences in simulated output for a given domain that pertain to the area covered by individual RiverWare objects. For purposes of this discussion the

modeled region is grouped into Upper and Lower sections which correspond to the regions defined by the Cochiti MODFLOW model and the Upper Albuquerque MODFLOW model, respectively. Summed river gain/loss comparisons for each of these regions (Upper and Lower) are also provided.

Head difference contours between the RW-MF Linked model and the MFOnly models were generated on the MODFLOW grids, contours are shown at specified dates pertaining to peak, average, and low flows observed in 1999-2000 in Figures 4.23 and 4.24.

Figure 4.17) MODFLOW General Head Boundary Flux/MODFLOW Lateral Boundary Flux for the Upper Portion of the Cochiti to Central Models 1999-2000. A summed *GHB* Flux at the MFOnly model lateral boundaries is displayed for all the *GHB* cells associated with a RiverWare **GroundWater** object. The MODFLOW Lateral Boundary Flux is displayed for each **GroundWater** object in the RW-MF Linked model. **GroundWater** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **GroundWater** object are listed in Table 4.5.

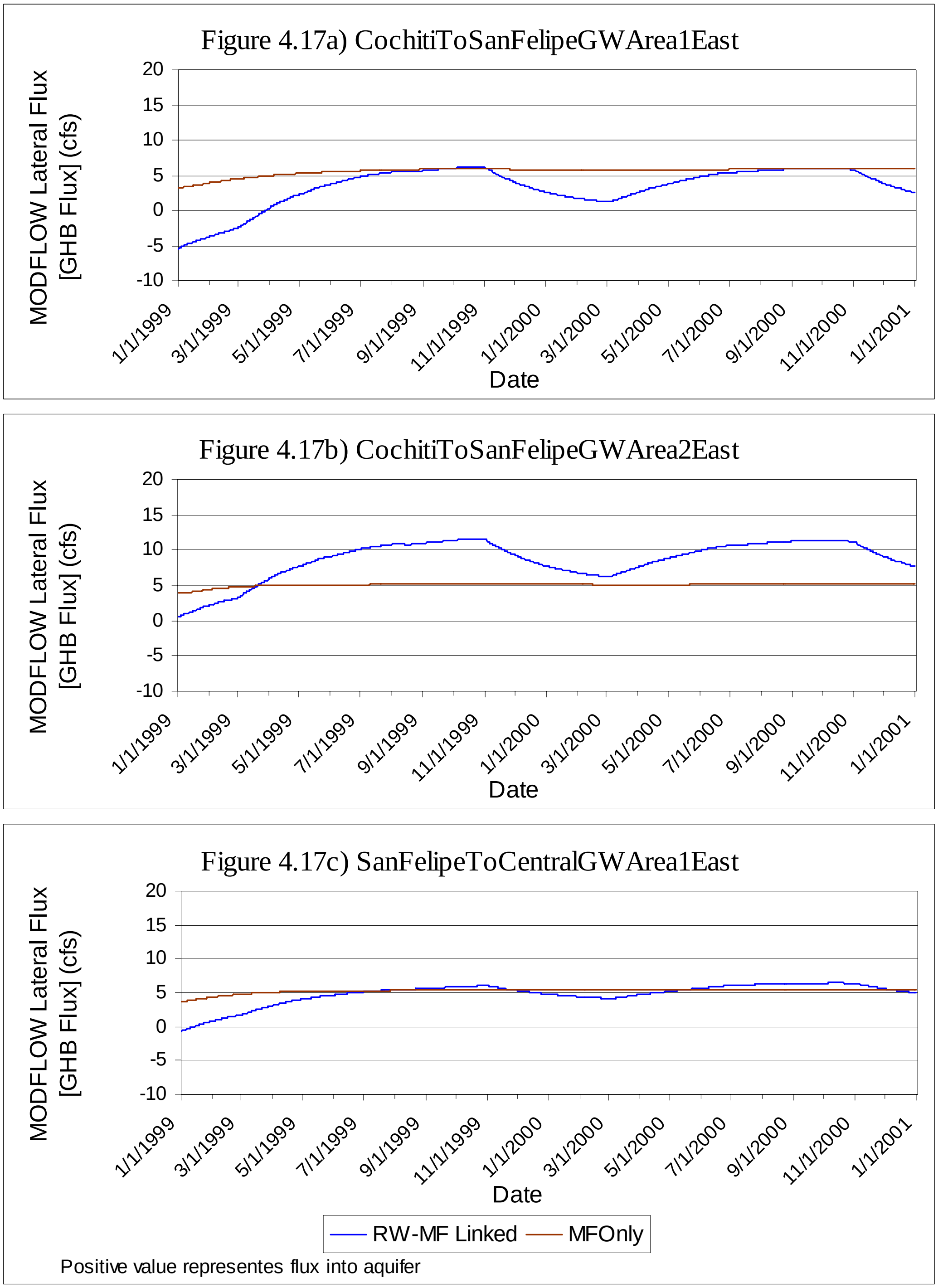


Figure 4.17 cont.) MODFLOW General Head Boundary Flux/Lateral Boundary Flux for the Upper Portion of the Cochiti to Central Models 1999-2000. A summed *GHB* Flux at the MFOnly model lateral boundaries is displayed for all the *GHB* cells associated with a RiverWare **GroundWater** object. The MODFLOW Lateral Boundary Flux is displayed for each **GroundWater** object in the RW-MF Linked model. **GroundWater** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **GroundWater** object are listed in Table 4.5.

Figure 4.17d) CochitiToSanFelipeGWArea1West

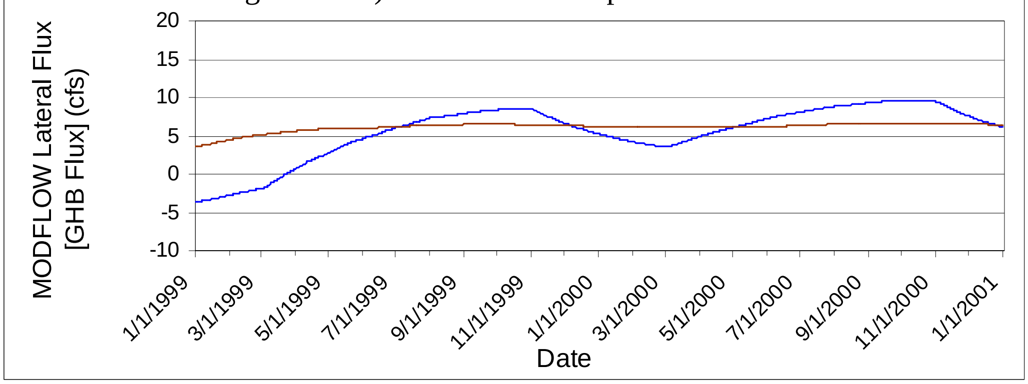


Figure 4.17e) CochitiToSanFelipeGWArea2West

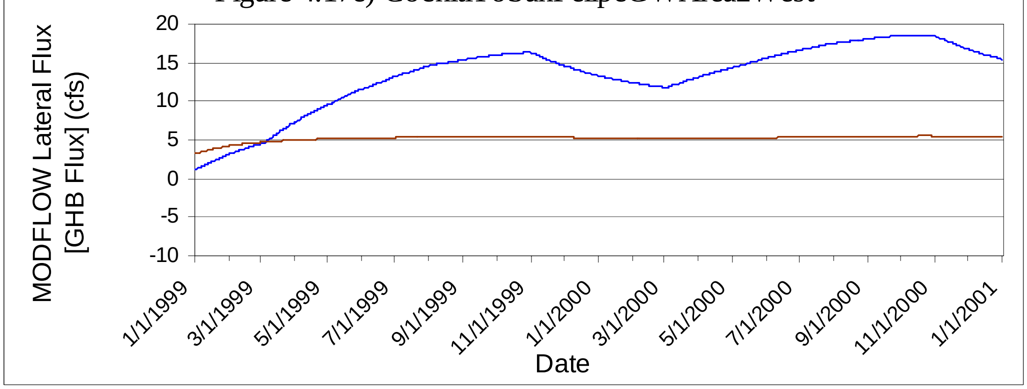


Figure 4.17f) SanFelipeToCentralGWArea1East

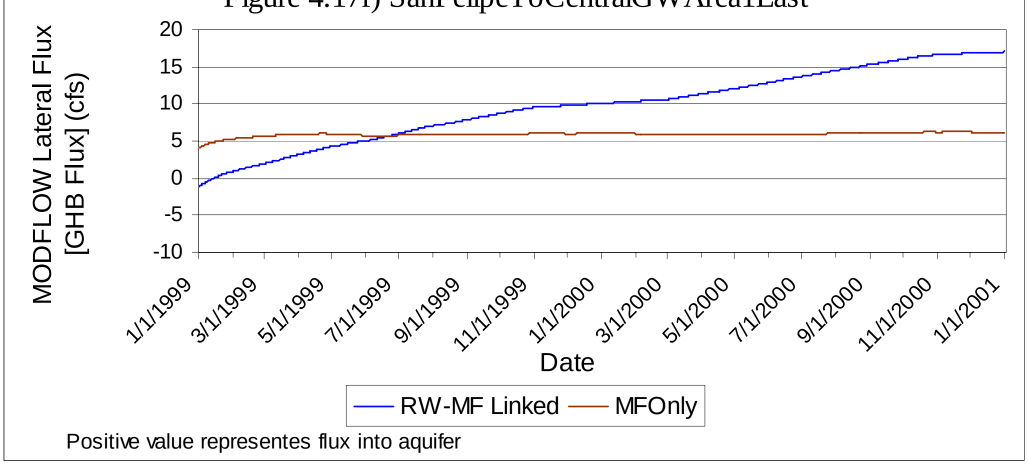


Figure 4.18) MODFLOW General Head Boundary Flux/Lateral Boundary Flux for the Lower Portion of the Cochiti to Central Models 1999-2000. A summed *GHB* Flux at the MFOnly model lateral boundaries is displayed for all the *GHB* cells associated with a RiverWare **GroundWater** object. The MODFLOW Lateral Boundary Flux is displayed for each **GroundWater** object in the RW-MF Linked model. **GroundWater** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **GroundWater** object are listed in Table 4.5.

Figure 4.18a) SanFelipeToCentralGWArea2East

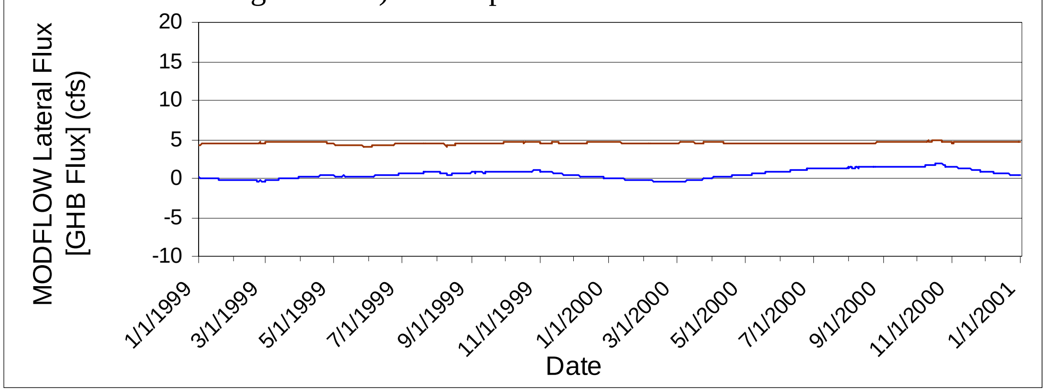


Figure 4.18b) SanFelipeToCentralGWArea3East

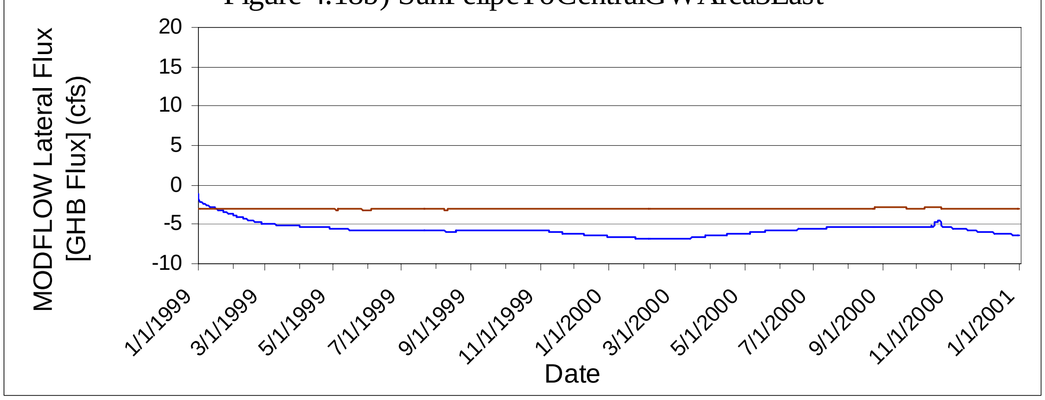


Figure 4.18c) SanFelipeToCentralGWArea4East

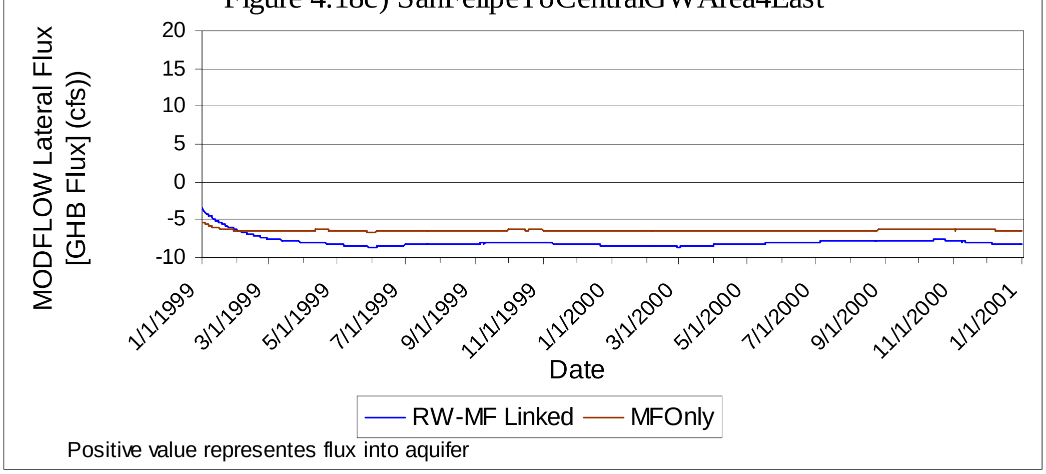
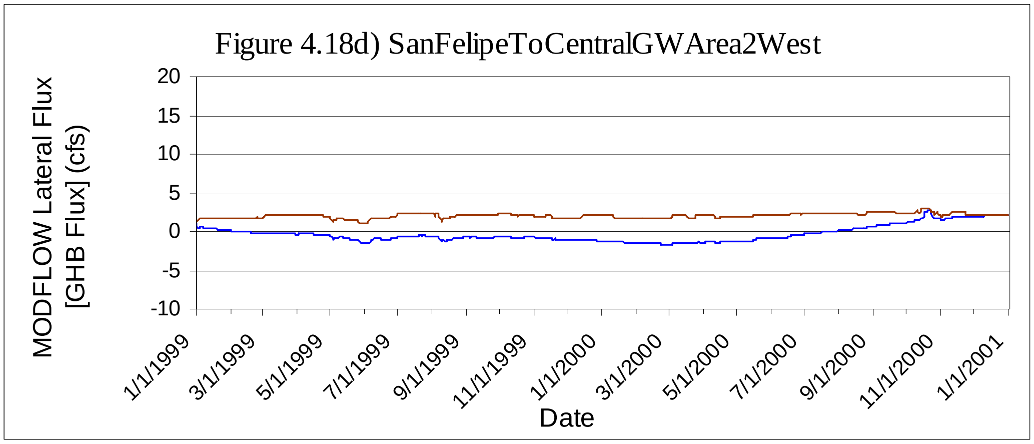
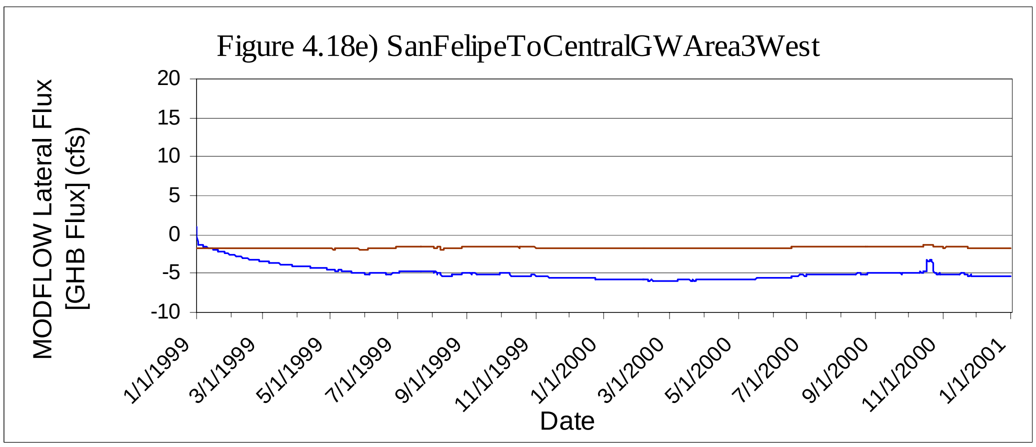


Figure 4.18 cont) MODFLOW General Head Boundary Flux/Lateral Boundary Flux for the Lower Portion of the Cochiti to Central Models 1999-2000. A summed *GHB* Flux at the MFOnly model lateral boundaries is displayed for all the *GHB* cells associated with a RiverWare **GroundWater** object. The MODFLOW Lateral Boundary Flux is displayed for each **GroundWater** object in the RW-MF Linked model. **GroundWater** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **GroundWater** object are listed in Table 4.5.





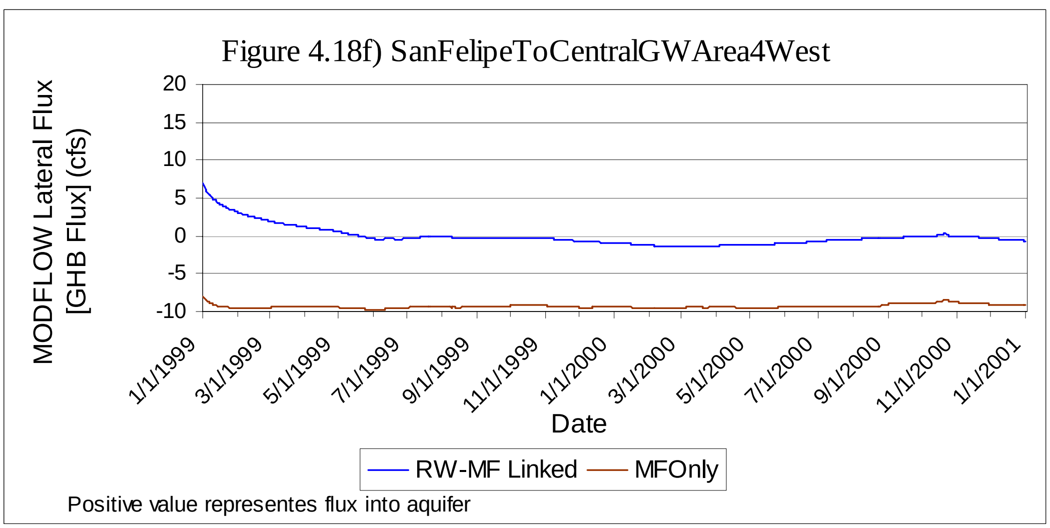


Figure 4.19) River Seepage/MODFLOW GainLoss for the Upper Portion of the Cochiti to Central Models 1999-2000. For the MFOnly model, the total summed *RIV* Seepage is displayed for all *RIV* cells associated with a RiverWare **Reach** object. For the RW-MF Linked model, the MODFLOW GainLoss is displayed for each **Reach** object. **Reach** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **Reach** object are listed in Table 4.5.

Figure 4.19a) CochitiToSanFelipeSeepageArea1

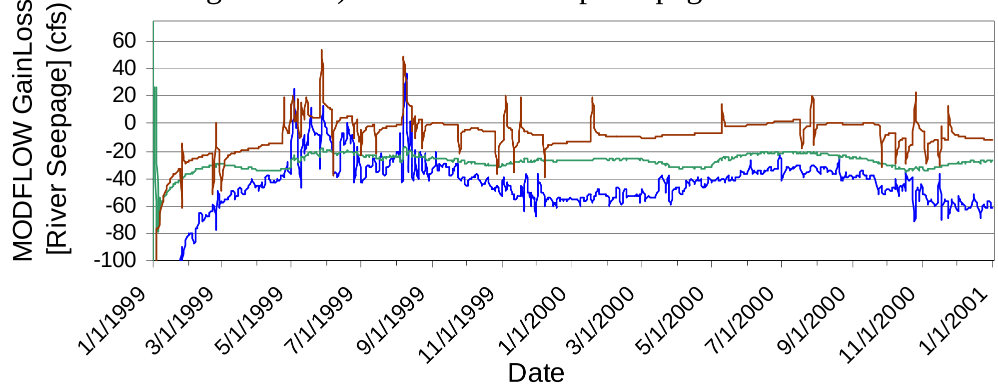


Figure 4.19b): CochitiToSanFelipeSeepageArea2

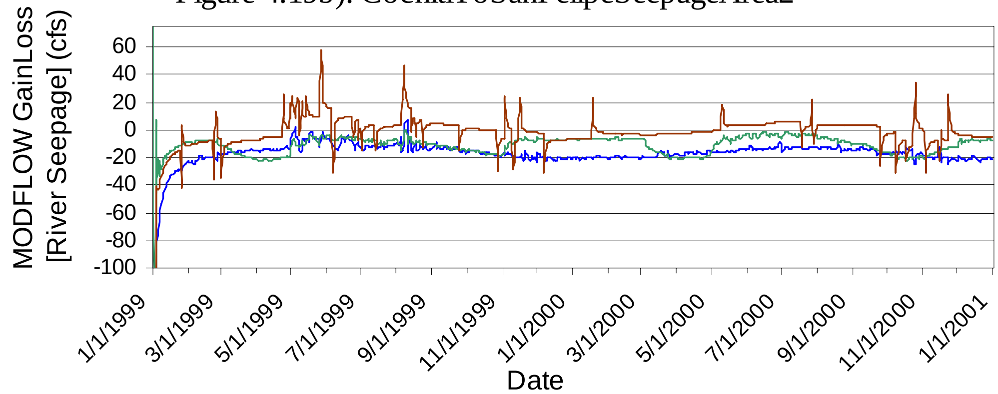


Figure 4.19c): SanFelipeToCentralSeepageArea1

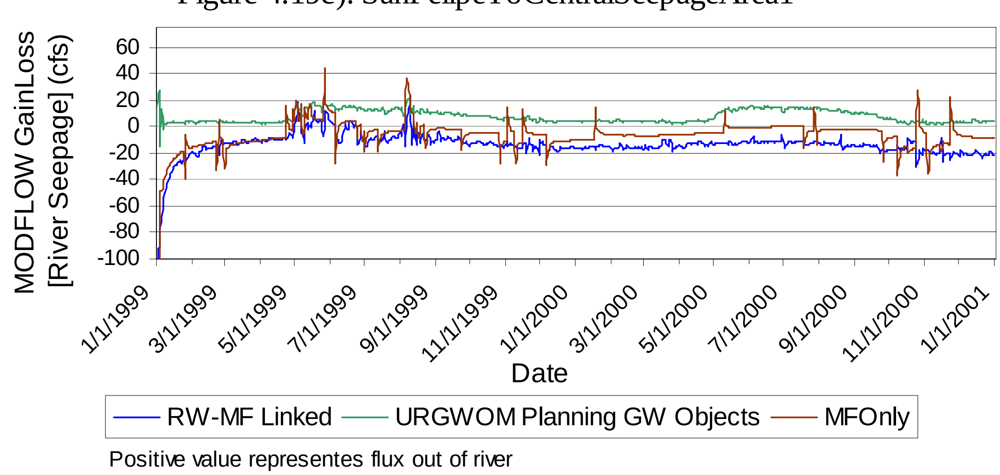
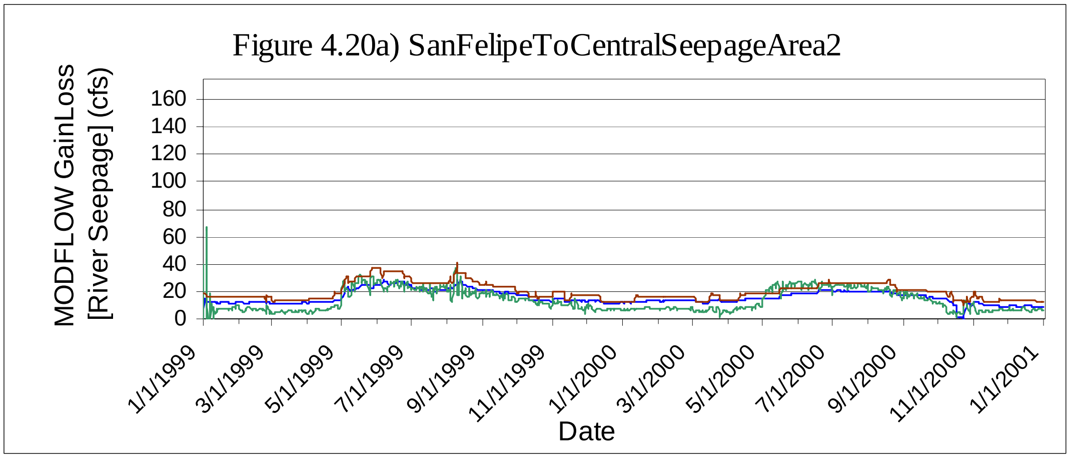
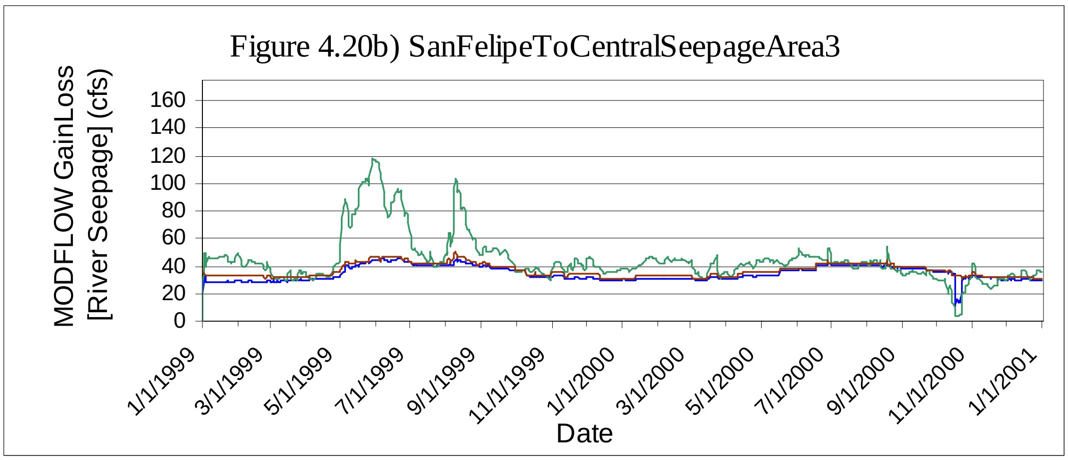


Figure 4.20) River Seepage/MODFLOW GainLoss for the Lower Portion of the Cochiti to Central Models 1999-2000. For the MFOnly model, the total summed *RIV* Flux is displayed for all *RIV* cells associated with a RiverWare **Reach** object. For the RW-MF Linked model, the MODFLOW GainLoss is displayed for each **Reach** object. **Reach** object locations are shown Figure 4.16 and the MODFLOW cells associated with a given **Reach** object are listed in Table 4.5.





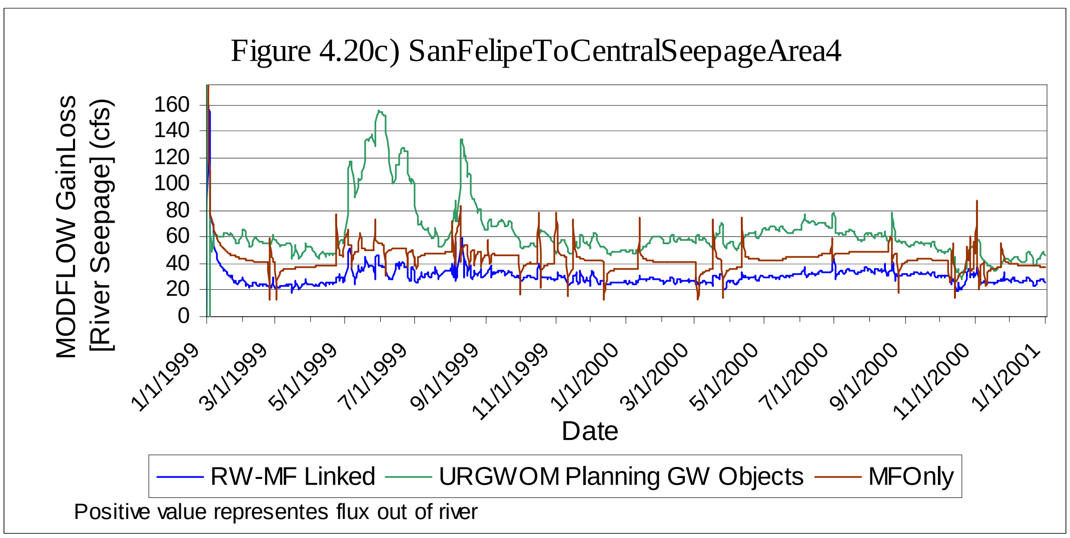


Figure 4.21) River Seepage/MODFLOW GainLoss Cochiti to Central 1999-2000. Total River Seepage is displayed over each reach Cochiti and Upper Albuquerque. For the MFOnly model, the total summed *RIV* Flux is displayed for the Upper and Lower regions of the model. For the RW-MF Linked and URGWOM Planning GW Objects models the MODFLOW GainLoss [River Seepage] displayed is the sum of the values from three **Reaches** within each region. For the URGWOM Planning model the MODFLOW GainLoss [River Leakage] displayed is for a single **Reach** in each region. **Reach** object locations are shown Figure 4.16.

Figure 4.21a) Cochiti to San Felipe Reach

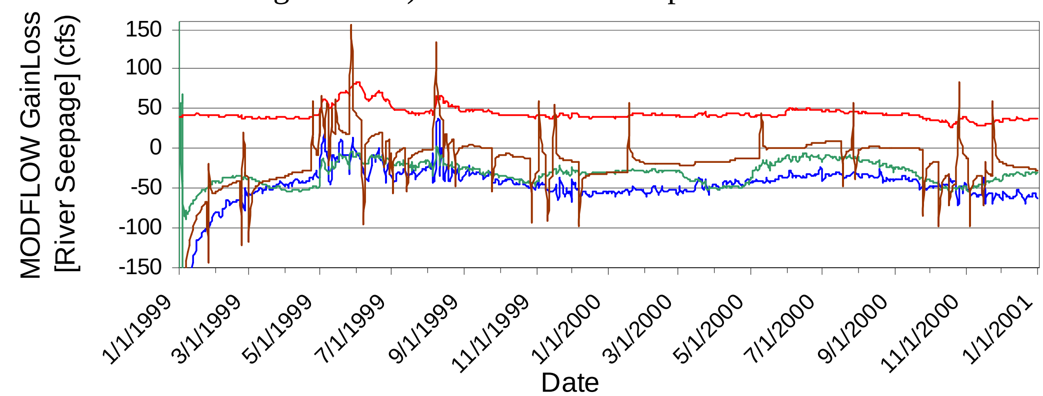


Figure 4.21b) San Felipe to Central Reach

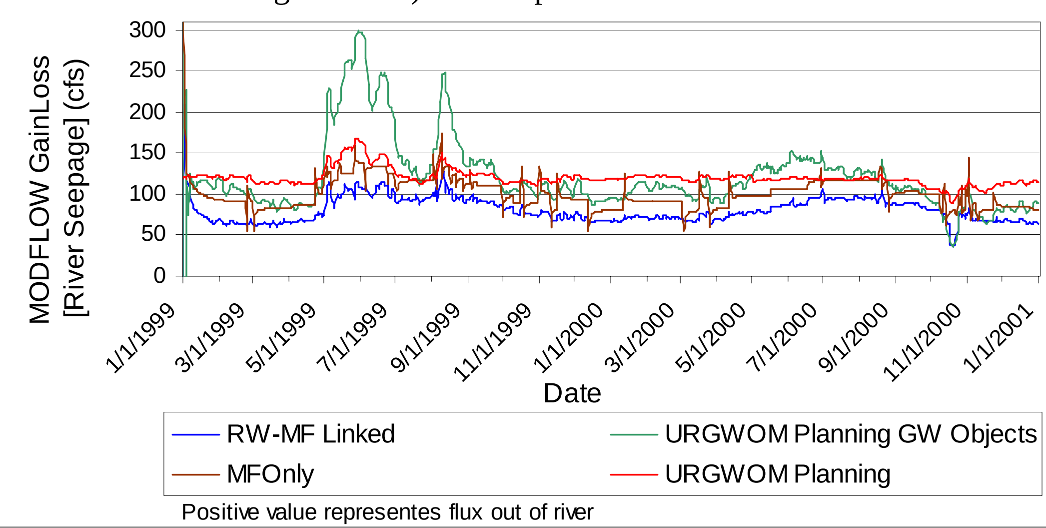


Figure 4.22) MODFLOW Local Return Flow/RiverWare Drain Inflows for the Cochiti to Central Models 1999-2000. Inflow for each drain is displayed by RiverWare object. For the MFOnly model, inflow into each drain (river segment) is displayed for the associated RiverWare **Reach** object. **Reach** object locations are shown Figure 4.16 and the MODFLOW segment associated with a given **Reach** object is listed in Table 4.5.

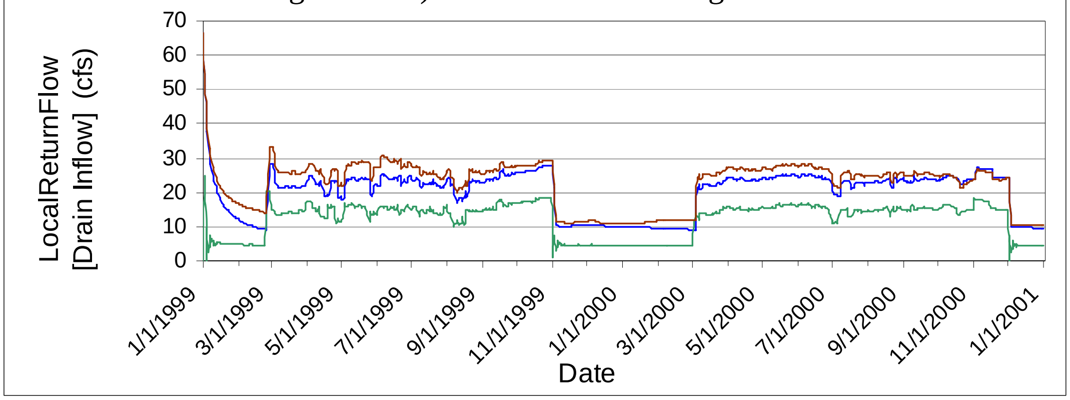


Figure 4.22a) EastSideSantoDomingoDrain

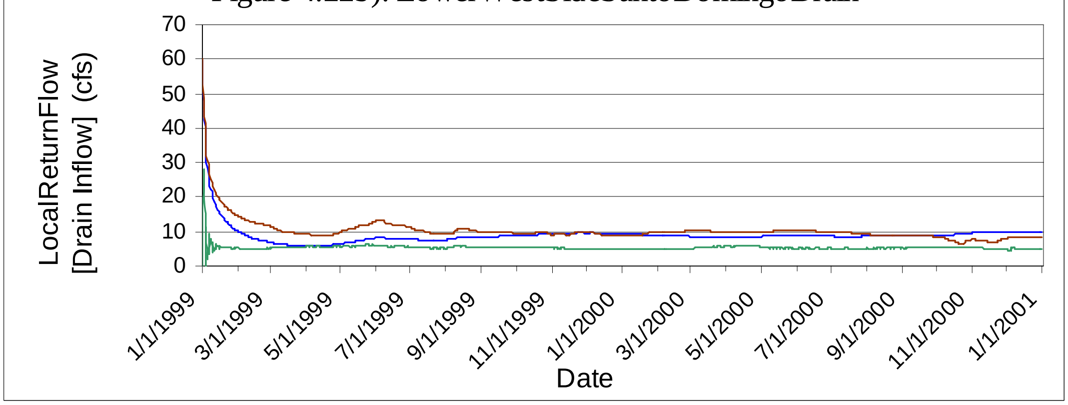


Figure 4.22b): LowerWestSideSantoDomingoDrain

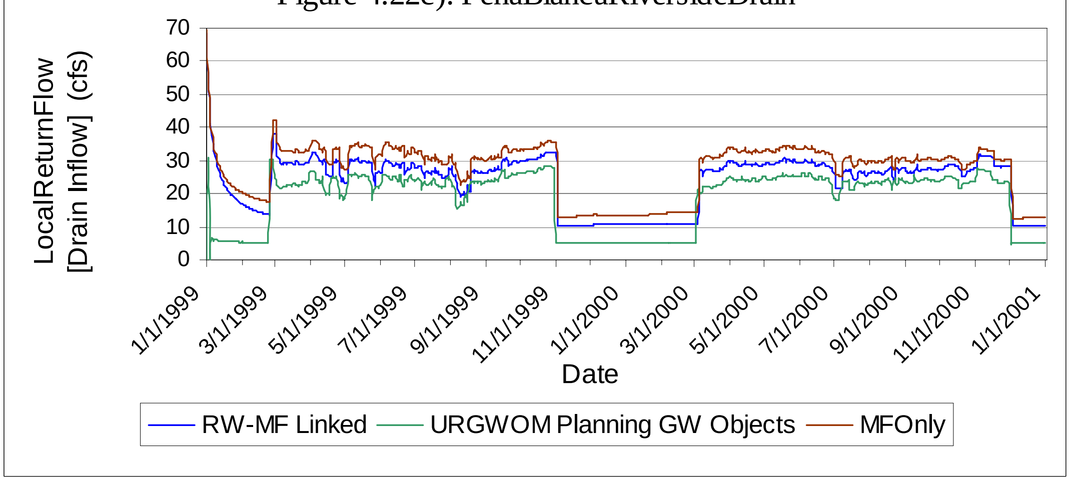


Figure 4.22c): PenaBlancaRiversideDrain

Figure 4.22cont) MODFLOW Local Return Flow /RiverWare Drain Inflows for the Cochiti to Central Models 1999-2000. For the MFOnly model, inflow into each drain (river segment) is displayed for the associated RiverWare **Reach** object. **Reach** object locations are shown Figure 4.16 and the MODFLOW segment associated with a given **Reach** object is listed in Table 4.5.

Figure 4.22d) SanFelipeToCentralDrainWest1

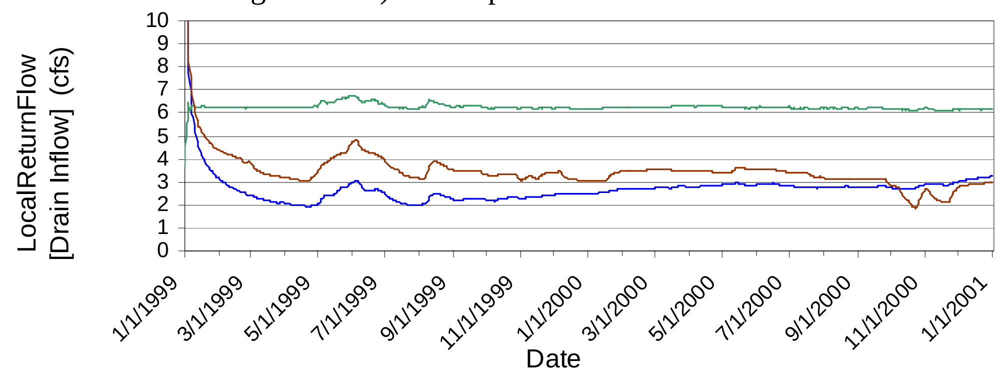


Figure 4.22e) SanFelipeToCentralDrainEast:Reach4

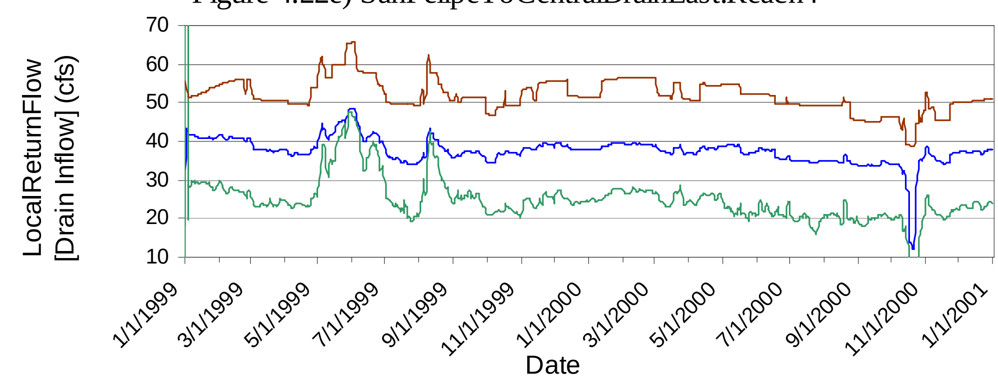


Figure 4.22f) SanFelipeToCentralDrainWest4

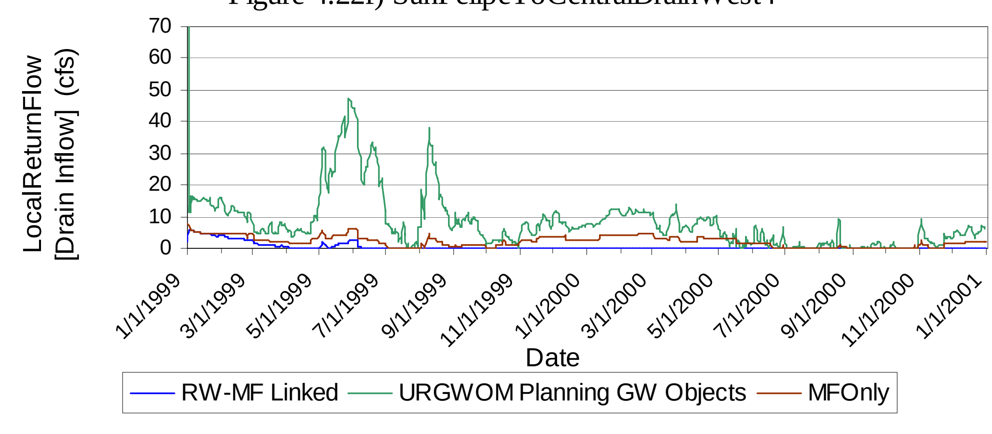


Figure 4.23) Head Difference – Upper Portion of the Cochiti to Central Models 1999-2000 (Cochiti). MODFLOW grid plan view is shown with color contours of the head difference between RW-MF Linked and MFOnly models (RW-MF Linked minus MFOnly). Color contours are shown for nominal dates in 1999-2000: peak flow event 5-30-1999, average flow event 9-1-2000, and low flow event 10-19-2000.

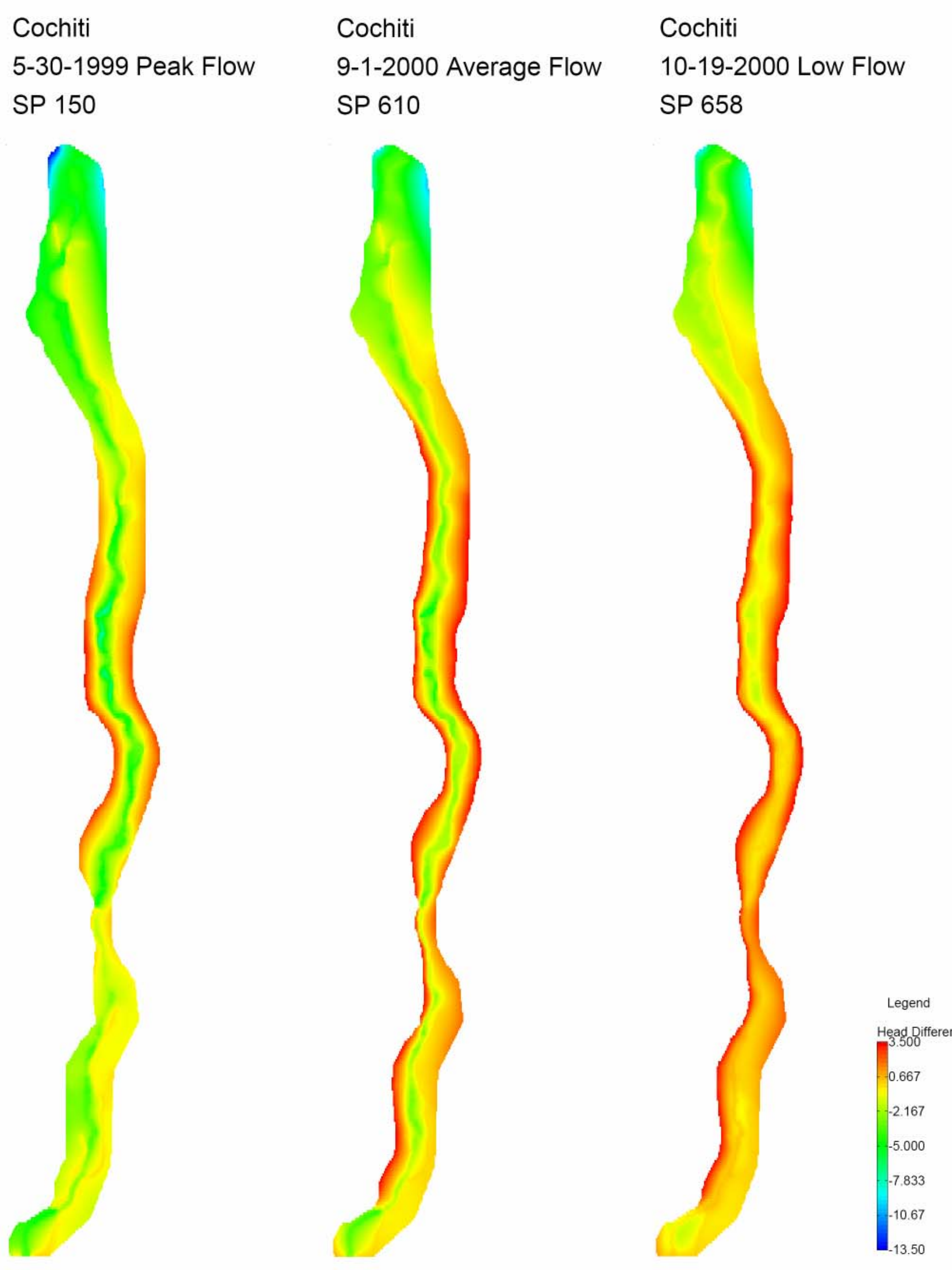


Figure 4.24a) Head Difference – Lower Portion of the Cochiti to Central Models 1999-2000 (UpperAlbuquerque). MODFLOW grid plan view is shown with color contours of the head difference between RW-MF Linked and MFOnly models (RW-MF Linked minus MFOnly). Color contours are shown for nominal dates in 1999-2000: peak flow event 5-30-1999, average flow event 9-1-2000, and low flow event 10-19-2000.

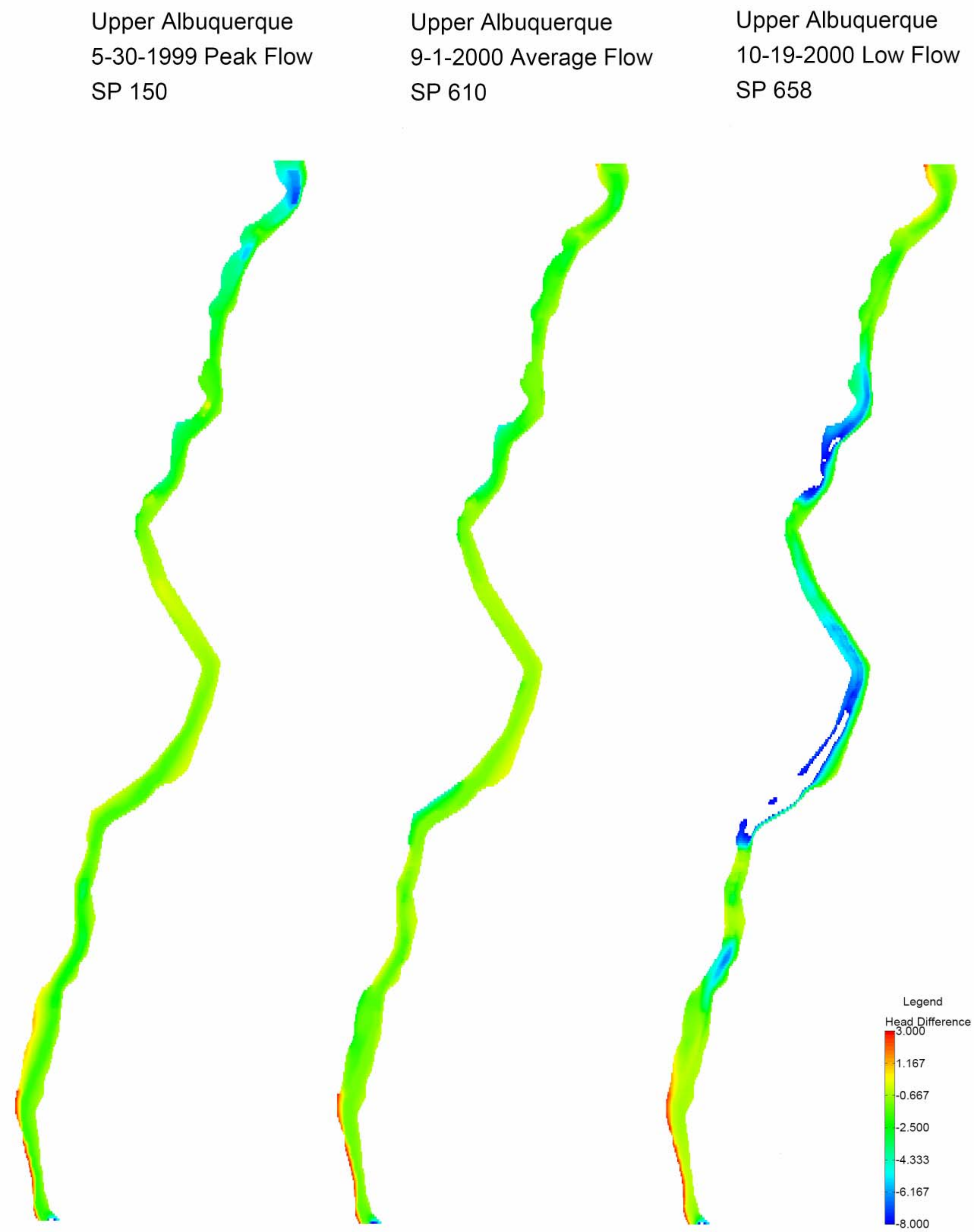
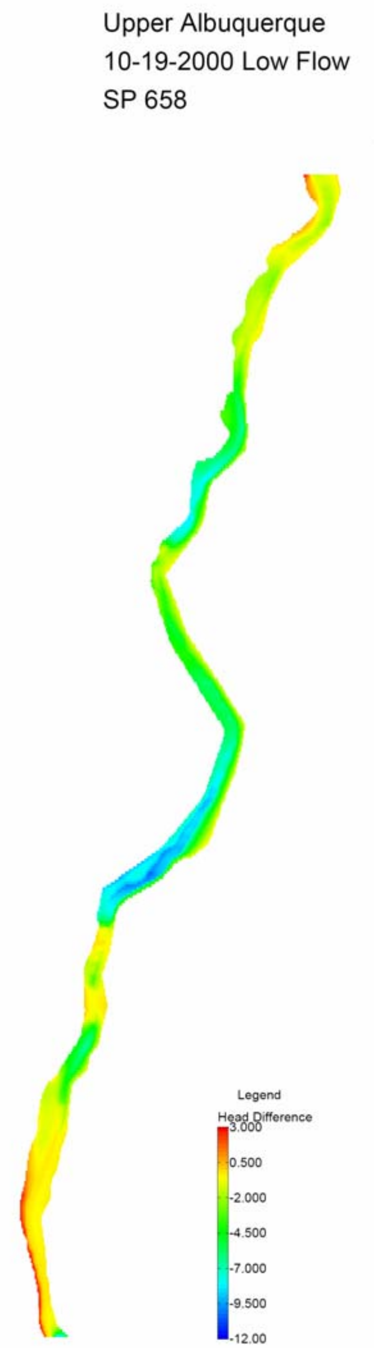


Figure 4.24b) Head Difference – Lower Portion of the Cochiti to Central Models 1999-2000 (UpperAlbuquerque). MODFLOW grid plan view is shown with color contours of the head difference between RW-MF Linked and MFOnly models (RW-MF Linked minus MFOnly). Color contours are shown for nominal dates in 1999-2000: low flow event 10-19-2000. Note: the scale shown in this figure is greater than the scale in Figure 4.24a.



4.3.1.1 *GHB* Package Comparison

Figures 4.17 and 4.18 display the fluxes calculated by the MODFLOW general head boundary package plotted against time for the RW-MF Linked and MFOnly models. One plot is shown for each of the **GroundWater** objects in the Upper and Lower portions of the modeled region. From the plots it is evident that the initial calculated lateral fluxes differ between the RW-MF Linked and MFOnly models. For example in Figure 4.17a, the fluxes for January 1, 1999 are -5.46 (RW-MF Linked) and 3.16 cfs (MFOnly). This difference in observed initial lateral fluxes implies that the initial heads set on the RW-MF Linked model **GroundWater** objects are not consistent with the boundary heads set in the MFOnly model *GHB* package as used in the MFOnly model. This inconsistency is due to adjustments made to the initial elevations on the **GroundWater** objects in the RiverWare model. The initial input elevations were modified by the USGS, during calibration of the URGWOM Planning GW Objects model 1999-2000 and these changes were carried over into the RW-MF Linked 1999-2000. Additionally, the differences in the lateral flux trend as observed throughout the run are likely due to the use of static *GHB* boundary heads (the boundary heads are the same in every time-step) for the MFOnly model, versus the applied dynamic boundary heads in the RW-MF Linked model (these heads vary by time-step and dependent on the elevation in the RiverWare **GroundWater** objects). Overall, the lateral fluxes calculated in the RW-MF Linked model tend to be larger than those calculated by the MF Only model, with the direction of flux towards the aquifer in the Upper portion of both models and in the Lower portion of both models predominately out of the aquifer. This suggests that the difference between the head in the aquifer and the boundary head is greater for the RW-MF Linked model than for the MFOnly model. An exception to these observations is noted for the SanFelipeToCentralGWArea4West object domain. From discussions with the NMISC and USGS, it is suspected that the MODFLOW model does not accurately quantify the physical processes in the region defined by the SanFelipeToCentralGWArea4West object and is the likely reason for the noted discrepancy.

Another input difference between the RW-MF Linked and MFOnly models that influences the calculated lateral boundary flux is the handling of irrigation groundwater returns (e.g. the link shown between the CochitiToSanFelipeEastsideCanalDeepSeep object and the CochitiToSanFelipeGWArea1West object in Figure 4.16a is an irrigation-surface water return to groundwater). These returns are only represented in the RW-MF Linked model and not in the MFOnly model. The influence of these returns can be seen in the plots especially in the Upper portion of the model. The irrigation returns occur March through October and an increase in flux to the aquifer is noted during the specified time period (Figure 4.17).

While the relative differences between the lateral fluxes observed for the two models tend to be significant, the actual fluxes themselves are at least an order of magnitude smaller than the river/aquifer gain/loss fluxes discussed below. Thus, these differences are not likely to significantly impact estimates of river seepage, which are of primary concern in the river operations.

4.3.1.2 *RIV* Package Comparison

Figures 4.19 and 4.20 display gain/loss (a.k.a. seepage) between the river and the aquifer rates plotted against time for the RW-MF Linked, MFOnly, and the URGWOM Planning GW Objects models. One plot (a,b,c) is shown for each of the **Reach** objects in the Upper and Lower sections of the modeled region. The URGWOM Planning GW Objects model is not discussed in this Section. Figure 4.21 shows the total gain/loss summed over all the **Reaches** in the Upper and Lower sections of the models. A similar seepage trend is observed in both the MFOnly and RW-MF Linked model outputs with time. Differences in the modeled seepage flux rates between the RW-MF Linked and MFOnly are apparent, but in both the RW-MF Linked and MFOnly models, the river is gaining in the Upper portion of the model and is losing in the Lower portion of the models (Figure 4.21). Several factors contribute to the differences in river/aquifer gain/loss calculated by the two models. One reason for this discrepancy in the calculated river/aquifer gain/losses is due to a difference in the *RIV* stage inputs between the two models. In the RW-MF Linked model, river flow in the RiverWare portion of the model changes on a daily basis and thus the stages used in the *RIV* package calculations change on a daily basis. In contrast, in the MFOnly model, stages used are set at discrete river flow rates which do not necessarily change on a daily basis (see Section 4.2.1.1 for a description for the *RIV* package input values). These variations in model inputs are clearly visible in Figure 4.20 parts a and b, in which the calculated RW-MF Linked model seepage curve is much smoother than the MFOnly model seepage curve. It is believed that the Lower portion of the Cochiti to Central region has more of a groundwater/surface-water hydraulic connection than the Upper portion of the model. This is why the model input differences are more accentuated in the Lower region.

Another factor influencing the calculated river seepage is the head in the aquifer. From Figures 4.23 and 4.24 it is apparent that there is a difference between the position of the potentiometric surface in the two models. In general, as shown in Figures 4.23 and 4.24 the elevation of the water table in the cells that contain *RIV* boundaries tends to be higher in the MFOnly model than in the RiverWare model. Since this elevation may be used in the river seepage calculation (see *RIV* package equations in Section 3.3.1), it may be a reason for the difference in observed seepages.

One clear advantage of the RW-MF Linked model is that no drastic seepage changes can be attributed to parameter input changes between stress periods, as is shown by the sharp peaks in the MFOnly model. Good examples of these peaks are visible in Figure 4.19b at 1/18/2000 and 5/10/2000 and Figure 4.20c at 11/1/1999 and 1/14/2000.

4.3.1.3 Local Inflow MF Return Comparison

Figure 4.22 displays LocalInflowMFReturn/Drain inflows (flow in a riverside drain at its confluence with the main channel of the Rio Grande) plotted against time for the RW-MF Linked and MFOnly models. One plot is shown for each of the **Reach** objects in the Cochiti to Central model. The MFOnly and RW-MF Linked models both show similar flow trends in drain returns with time. The calculated drain return flows are all lower in the RW-MF Linked model than in the MFOnly model. This trend is consistent with the uniformly lower heads observed in the RW-MF

Linked model (Figures 4.23 and 4.24). (See discussion on *GHB* package comparisons for further explanation).

An interesting note on drain flows in the Lower portion of the model is that the outputs from the drains closely mirror the input hydrograph of the main river channel (Figure 4.22). As discussed in Section 4.3.1.2 a greater hydraulic connection between the river and the aquifer is believed to be present in the Lower portion of the model versus the Upper portion of the model, and this appears to be true for the riverside drains as well. Thus, the difference in inputs for the *RIV* package (as described in the previous Section) has an influence on flow calculated in the riverside drains. As previously stated, in the RW-MF Linked model, flow in the river changes on a daily basis (based on input data), whereas in the MFOnly models flow follows a staircase hydrograph. These same trends are observed in the drains, where in the RW-MF Linked model drain flow closely matches the daily hydrograph and in the MFOnly model, drain flow closely matches the staircase function hydrograph. Since flow in the riverside drain mostly comprises intercepted river seepage (see description in Section 1.1), it makes sense that a variation in inputs for the river between the two models is reflected in the riverside drain flow.

4.3.1.4 Heads Differences - Linked and MFOnly models

Figures 4.23 and 4.24 present color contour plots for the head differences between the RW-MF Linked and MFOnly models. One plot is shown for specified dates of peak, low, and average flows for the Upper and Lower sections of the modeled region for 1999-2000. The difference displayed is for the RW-MF Linked model heads minus MFOnly model heads.

Heads in the Cochiti MFOnly model on average tend to be 5 feet higher than heads in Upper portion of the RW-MF Linked model directly beneath the river and about 3 feet lower along the east and west boundaries. Heads in the Upper Albuquerque MFOnly model on average tend to be about 2.5 feet higher than heads in the Lower portion of the RW-MF Linked model. The greatest head differences are observed directly beneath the river. Overall the head differences observed between Linked and MFOnly models were smaller during lower flow periods than during higher flow periods.

4.3.2 Conclusion

Overall, the differences between the RW-MF Linked and MFOnly models are considerably larger than anticipated. However, the trends observed for river seepage, lateral flux and drain return flows are similar between the RW-MF Linked and MFOnly models and the discrepancies noted in the calculated values may be attributed to differences in input parameters and model configurations, as discussed above.

4.4 Case Study 3: Historic Flow Comparison

This third case study compares three models of the Middle Rio Grande during two flow conditions, a typical/average river flow period (1999-2000) and a nominally low river flow period (1976-1977). This case study compares the models' outputs with one another, as well as with historic data.

4.4.1 Scenario 1 - Historic Average Flow Conditions 1999-2000

Historic data is available for four gages within the modeled region. (Gage locations are shown in Figures 4.14, 4.15, and 4.16). Three of the four gages are located in the main river channel (BlwCochiti, SanFelipe, and Central) and the fourth is located in the east side canal (CochitiCanAtSanFelipe). Figures 4.25 and 4.26 present flow hydrographs at each gage as taken from the URGWOM Planning 1999-2000, URGWOM Planning GW Objects 1999-2000, RW-MF Linked 1999-2000 models. Historic 1999-2000 flows at each gage are also included in these figures. Figure 4.26 shows flow in the San Felipe and Central gages for the year 2000 only.

Figure 4.25) Flow at Gages in Cochiti to Central Models for 1999-2000. In Figure a, all the three models have identical flow. In Figure b, the RW-MF Linked and URGWOM Planning GW Objects models have identical flow.

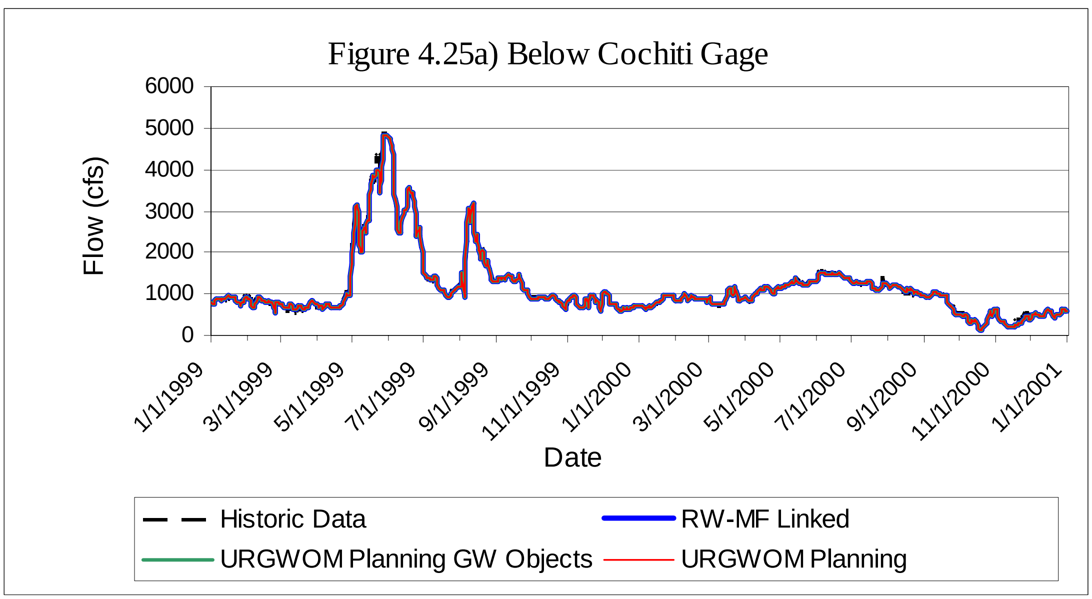
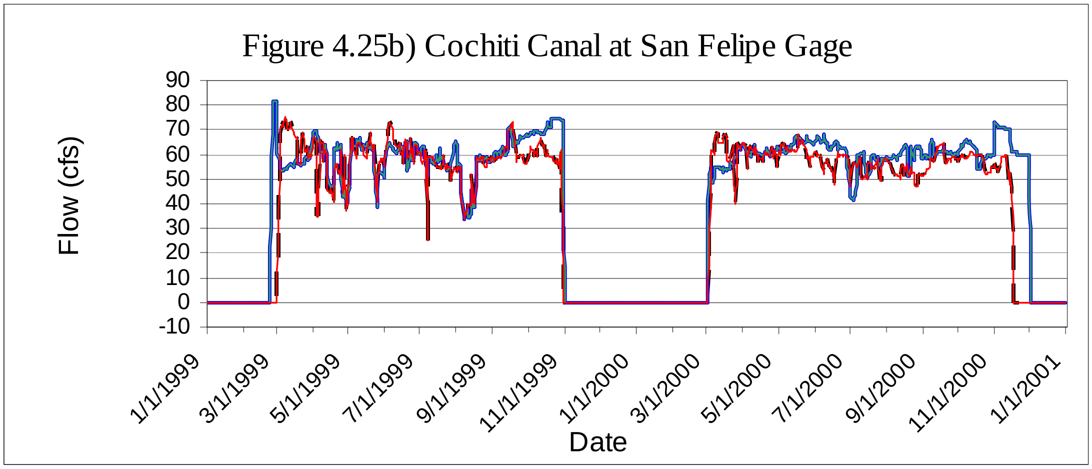
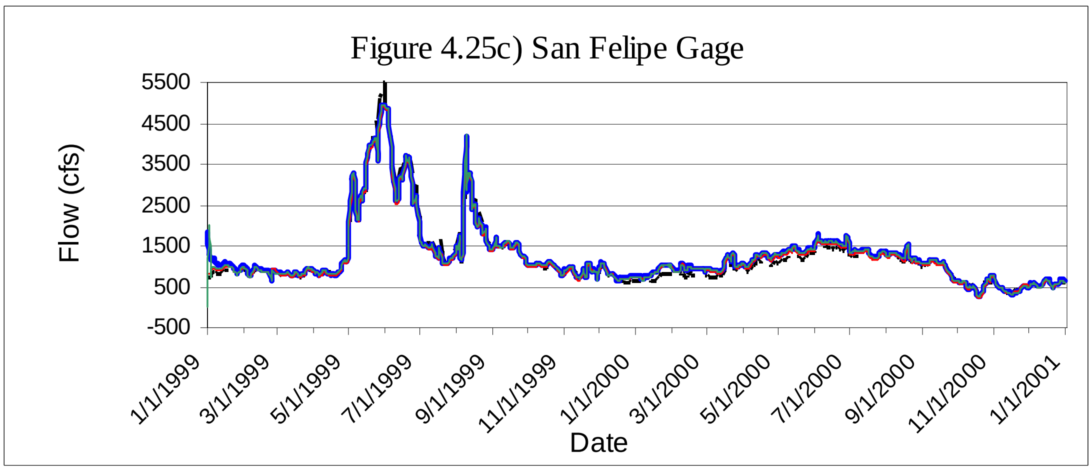


Figure 4.25 cont.) Flow at Gages in Cochiti to Central Models for 1999-2000. In Figure a, all the three models have identical flow. In Figure b, the RW-MF Linked and URGWOM Planning GW Objects models have identical flow.





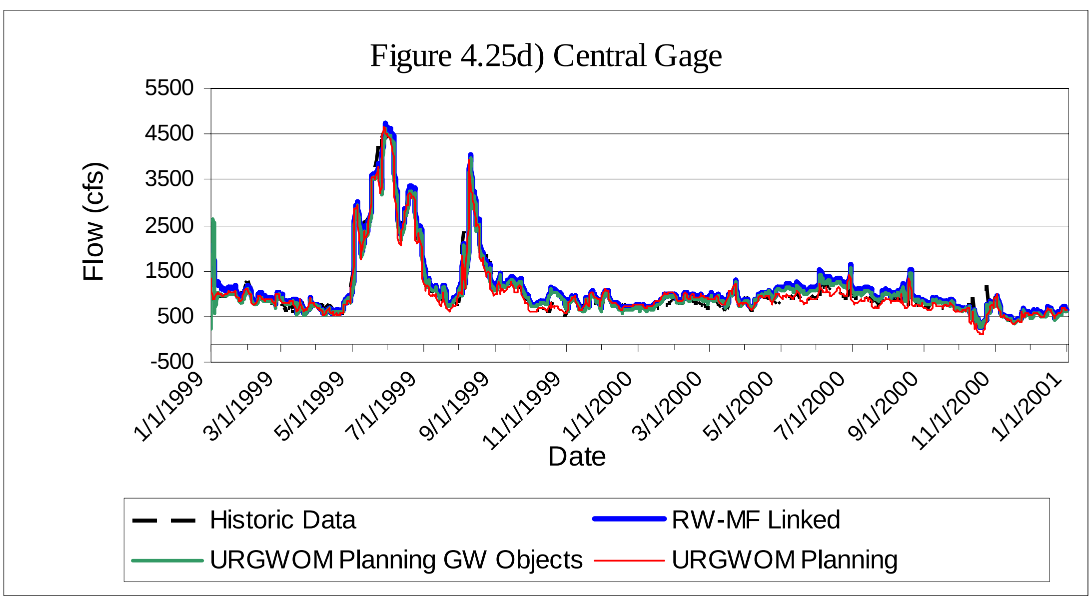


Figure 4.26) Flow at Gages in Cochiti to Central Models for 2000. In Figure a, all the three models have identical flow. In Figure b, the RW-MF Linked and URGWOM Planning GW Objects models have identical flow.

Figure 4.26a) Below Cochiti Gage

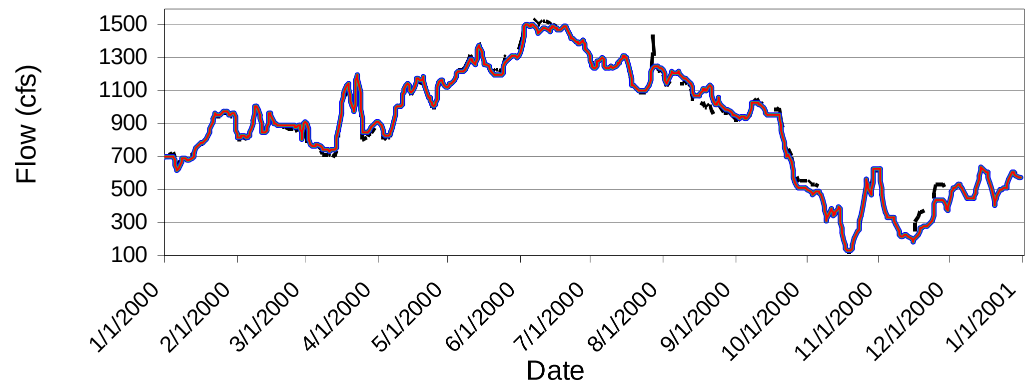


Figure 4.26b) Cochiti Canal at San Felipe Gage

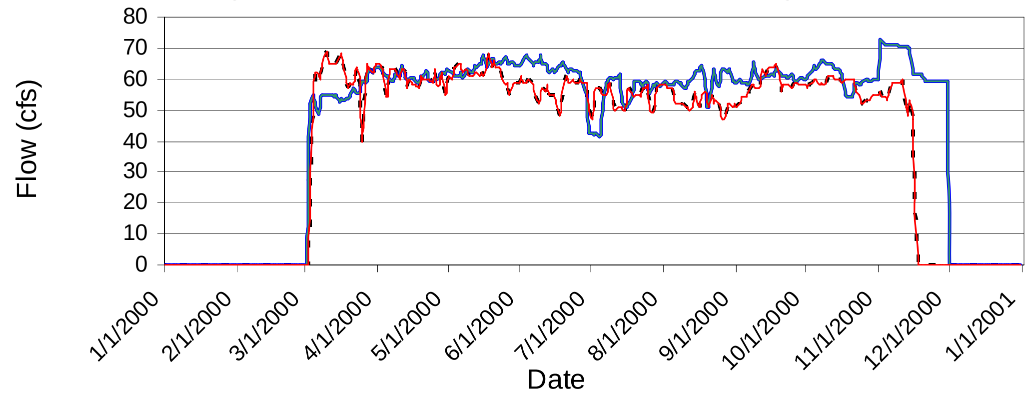


Figure 4.26c) San Felipe Gage

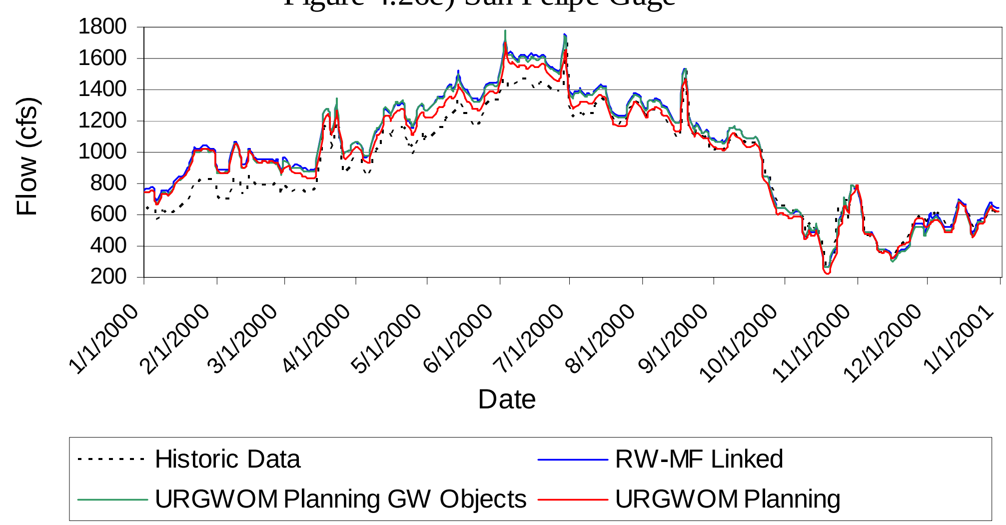
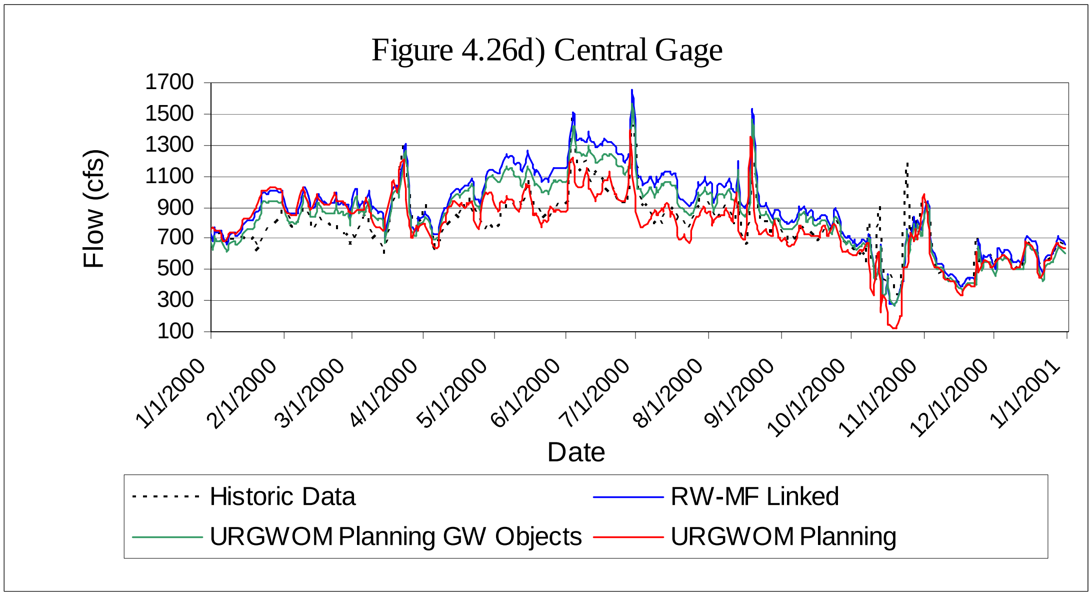


Figure 4.26 cont.) Flow at Gages in Cochiti to Central Models for 2000



River flow entering the region is exactly the same in all three models (inflow to the river is specified in the CochitiOutflowData object for the years of 1999-2000), and all three models match the historic gage data fairly well, with the most variation observed in the gage at the base of the model (Central gage). Overall, the URGWOM Planning model produces flows that match the historic record most closely, while the other two models produce flows that are similar to one another and tend to be slightly greater than historical flows.

As noted in the model description section, differences beyond the calculation of river gain/loss exist between the URGWOM Planning model and the two other models (RW-MF Linked and URGWOM Planning GW Objects). One model configuration difference is apparent by looking at the Cochiti Canal at San Felipe Gage plots. Since the Cochiti Canal at San Felipe gage is located in the canal, it is a good indicator of the flow differences caused by the differences in canal configurations between the models. From Figures 4.25b and 4.26b, the identical diversion schedule and canal configurations in the RW-MF Linked and URGWOM Planning GW Objects models are immediately obvious, since the two models produce the same curve. Likewise, the difference between the irrigation canal configuration in these two models when compared to the URGWOM Planning model is evident by the very different trends that these model produce (Figures 4.25b and 4.26b). Again by looking at Figure 4.25b, it is obvious that flow at the Cochiti Canal at San Felipe gage in the URGWOM Planning model matches historic flow very well. In fact, in the URGWOM Planning model, the actual flow calculated in this drain is adjusted so that flow into the gage will match historic data. A comparison between how well the URGWOM Planning model matches historic flows and how well the other two models match historic flows at this gage would be misleading, since the URGWOM Planning model's flow will always match historic data due to its configuration. Since flows produced at this gage in the URGWOM Planning GW Objects and RW-MF Linked models do not match extremely well with historic data, better calibration of the model in this canal to historic data could enhance model performance.

Overall, the RW-MF Linked and URGWOM Planning GW Objects models produce flows at the San Felipe and Central gages that are greater than historic flows Figures 4.25c, 4.25d, 4.26c, and 4.26d. However, both the RW-MF Linked and the URGWOM Planning GW Objects models are better able to capture the observed low flows in October 2000 than the URGWOM Planning model. They are also more consistent in that they tend to over-predict flows at these two gages. In contrast, the URGWOM Planning model alternates between over-prediction of flow (January Figure 4.26d) and under-prediction of flow (October Figure 4.26d).

The main difference between the URGWOM Planning GW Objects and RW-MF Linked models is the calculation of river/aquifer gain/loss. In the Cochiti reach the URGWOM Planning GW Objects model produces lesser gains to the river, and in the Upper Albuquerque reach it produces greater losses from the river than the RW-MF Linked model (Figure 4.21). This behavior indicates that in the URGWOM Planning GW Objects model, fluxes out of the river from the aquifer may be too great and may produce decreased river flows, or that the RW-MF Linked model may produce fluxes that are too small, and thus relatively elevated river flows. In either case there is a slight difference in flow due to the difference in estimated river/aquifer flux values and this is evident in Figure 4.26d, which shows flows produced by the URGWOM Planning GW objects as lower than those produced by the RW-MF Linked model.

For the Cochiti reach, a large difference in the calculated river gain/loss is evident in the URGWOM Planning model when compared to the other two models. In fact, the direction of flux as calculated in the URGWOM planning model is out of the river; however in the other two models flux is into the river (Figure 4.21). As described in the model description section, the URGWOM Planning model's river gain/loss calculation is based on a regression equation for which regression coefficients were created to match historic flow in this specific model setup. Additionally, several surface water features that contribute flow to the main river channel are not present in, or have different configurations than the URGWOM Planning model (e.g. PenaBlancaRiversideDrain is not present in URGWOM Planning model). Thus, it is suspected that the regression equation in this reach accounts for river contributions from these sources, and the value calculated by this equation would not actually represent river gain/loss between the river and the aquifer. Unlike in the Cochiti reach, the seepage estimates in the URGWOM Planning model for Upper Albuquerque reach are believed to be a produce an actual estimate of seepage. However, this value is while more realistic it is are not necessarily accurate and as shown in Figure 4.21b, the river seepage predicted by the regression equation tends to favor middle values and all the highs and lows are smoothed out.

4.4.2 Scenario 2: Historic Low Flow Conditions 1976-1977

The RW-MF Linked 1976-1977, URGWOM Planning Cochiti to Elephant Butte 1975-1999, and URGWOM Planning GW Objects 1976-1977 models as described in the model description section, were used in this comparison.

Figures 4.27 to 4.30 present flow at the four model gages during 1976-1977 at various scales. In part c of Figures 4.27 to 4.30, flow at the gages is displayed for the months of August, September, and October. In these months some of the lowest, as well as most varied (change in flow over a short time period is great), historic flows were recorded during the 1976-1977 time period. In all three models, flow at the top of the model at the Below Cochiti gage matches historic flow very well (Figure 4.27). The URGWOM Planning model flows recorded at the Cochiti Canal at San Felipe gage exactly match historical data, which differs from the flows produced by the URGWOM Planning GW Objects and RW-MF Linked models. As discussed previously, differences in the measured flow between the models at this gage are due to configuration differences in the drains (see discussion in Section 4.4.1). At the San

Felipe gage, flow calculated by all three models provides a reasonable approximation of historic data, with the RW-MF Linked model having the best fit for extremely low flows as seen in Figure 4.29c during the months of August (days 1-4), September (days 9-23), and October (days 10-20).

Modeled flows at the Central gage do not match historic record data as well as they do at the San Felipe gage (Figure 4.30). The URGWOM Planning GW Objects and RW-MF Linked models tend to over-estimate flow, while the URGWOM Planning model under estimates or over estimates flow in different portions of the run. In Figure 4.30c and 4.30d, it is apparent that flow is grossly over-predicted by all three models for periods (e.g. 8-30-1977 to 9-7-1977; 9-25-1977 to 10-10-1977; and 10-23-1977 to 11-1-1977). In all these cases the historic flow begins increasing after having been extremely low (less than 70 cfs) for multiple days. The flows produced by the models during these instances also increase, but at a much faster rate and by a larger amount than indicated in the historic record. During these time periods the RW-MF Linked and URGWOM Planning GW Objects models predict greater flows than the URGWOM Planning model, and all three models amplify slight changes in flow as observed by distinct multiple peaks in these relatively elevated predicted flows. This might indicate that canal returns may be too great during these periods, and better model performance might be achieved with some model calibration. A second parameter that could be calibrated for better model performance is evapotranspiration. Since, the evapotranspiration primarily occurs during the summer and fall months and is not active in the models during the winter, it may contribute to the calculated in-stream flow deviation from historic gage data.

Another explanation could be that the historic gage data is incorrect. In Figure 4.30b all three models match well with the historic flow for the first and last few months in 1977. However, the modeled flow diverges from historic data just after spike increases in flow (Figure 4.30c and d), so it is possible that the gage data at during these periods may be unreliable due to factors such as a shift in sediment in the channel from the spiked flow. Another observation regarding these instances is that the model produced flows reach peak flow a day or two before the historic record. This could indicate that the routing method selected and/or its configuration in the lower portion of this model may not sufficiently represent the physical in-channel flow process for this region.

Figure 4.27) Flow at Below Cochiti Gage in Cochiti to Central Models 1976-1977. All the three models have identical flow at this gage.

Figure 4.27a) Below Cochiti Gage

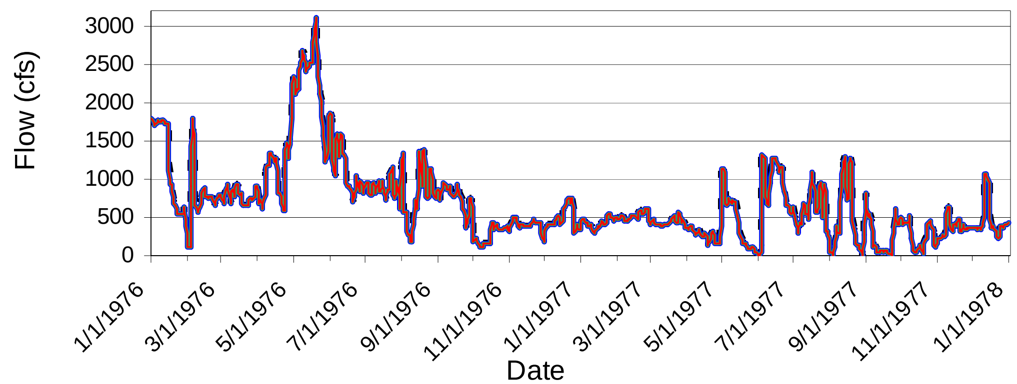


Figure 4.27b) Below Cochiti Gage

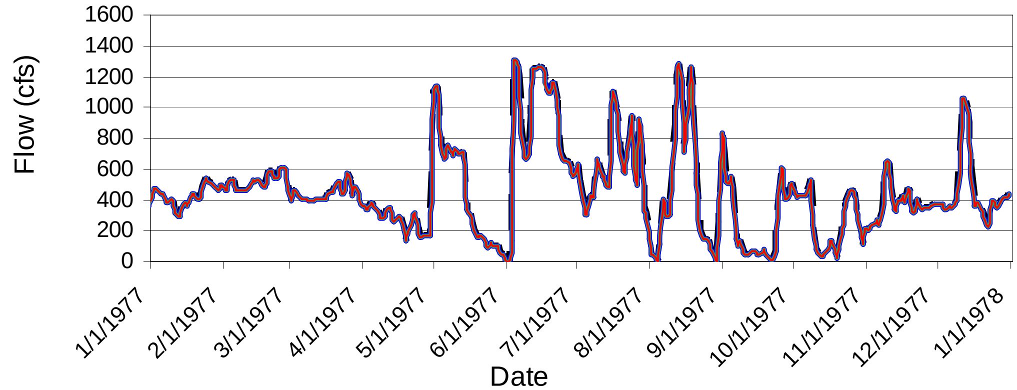


Figure 4.27c) Below Cochiti Gage

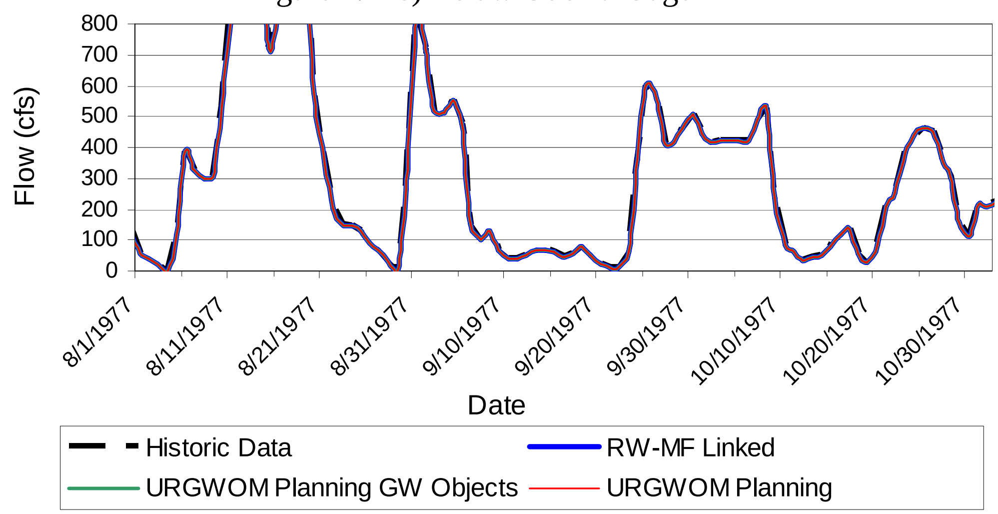
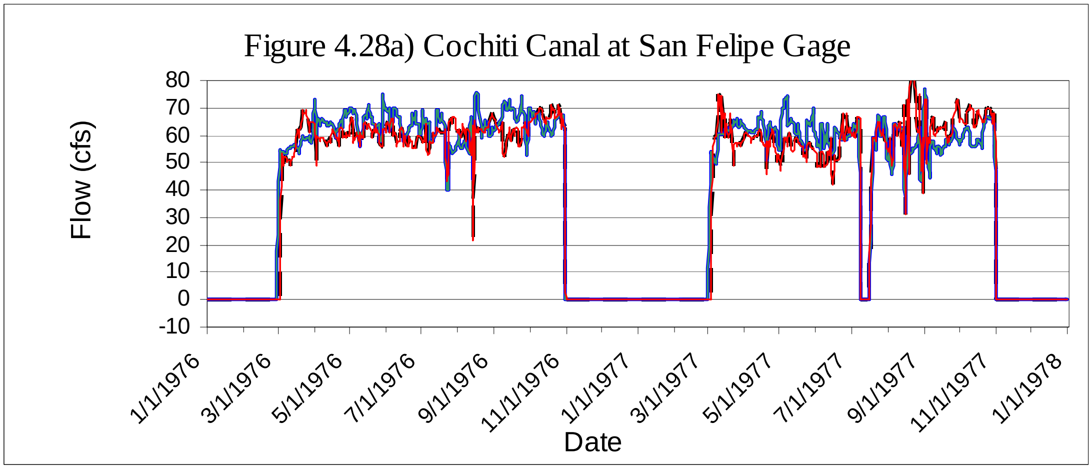
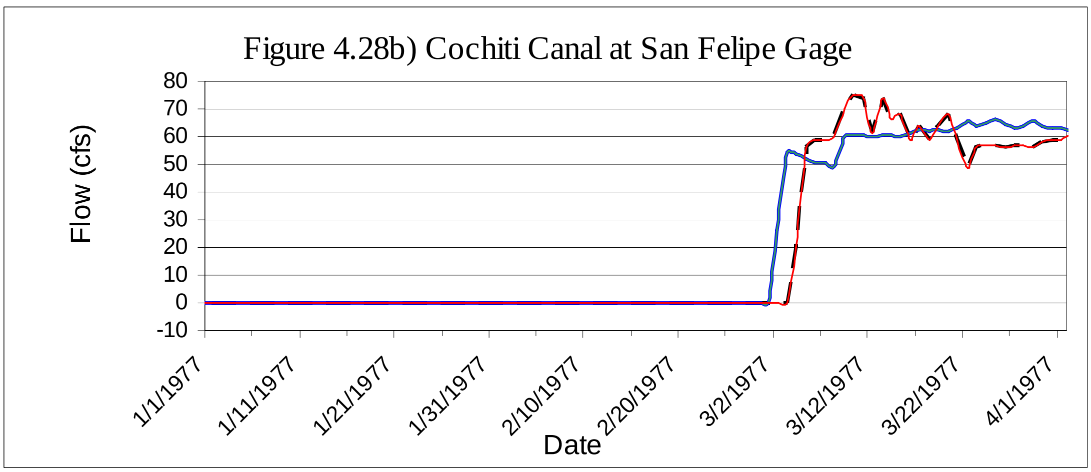


Figure 4.28) Flow at Cochiti Canal at San Felipe Gage in Cochiti to Central Models 1976-1977. The RW-MF Linked and URGWOM Planning GW Objects models have identical flow at this gage.





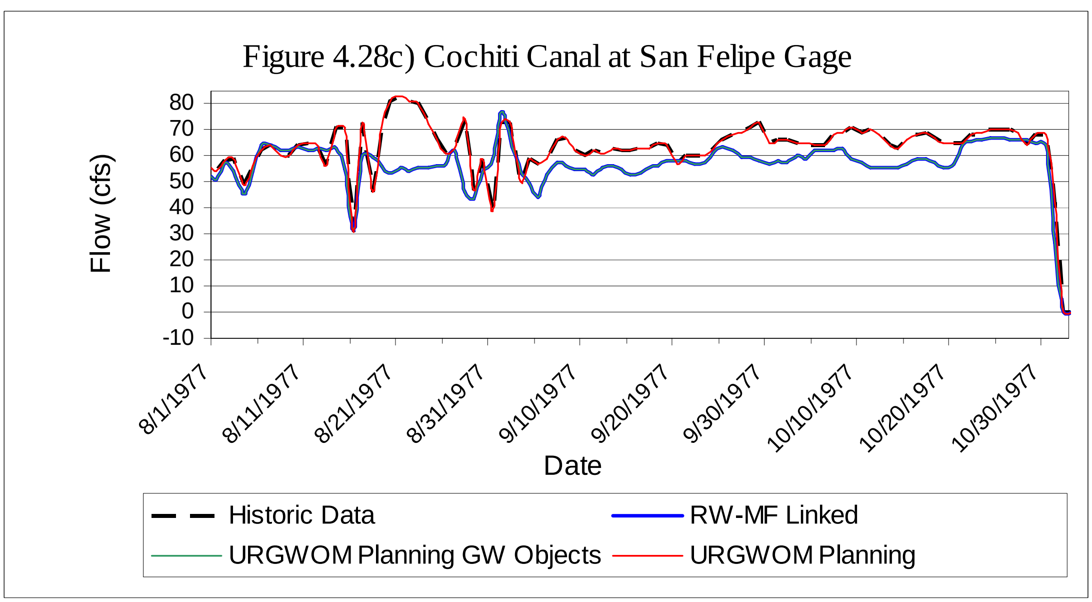


Figure 4.29) Flow at San Felipe Gage in Cochiti to Central Models 1976-1977.

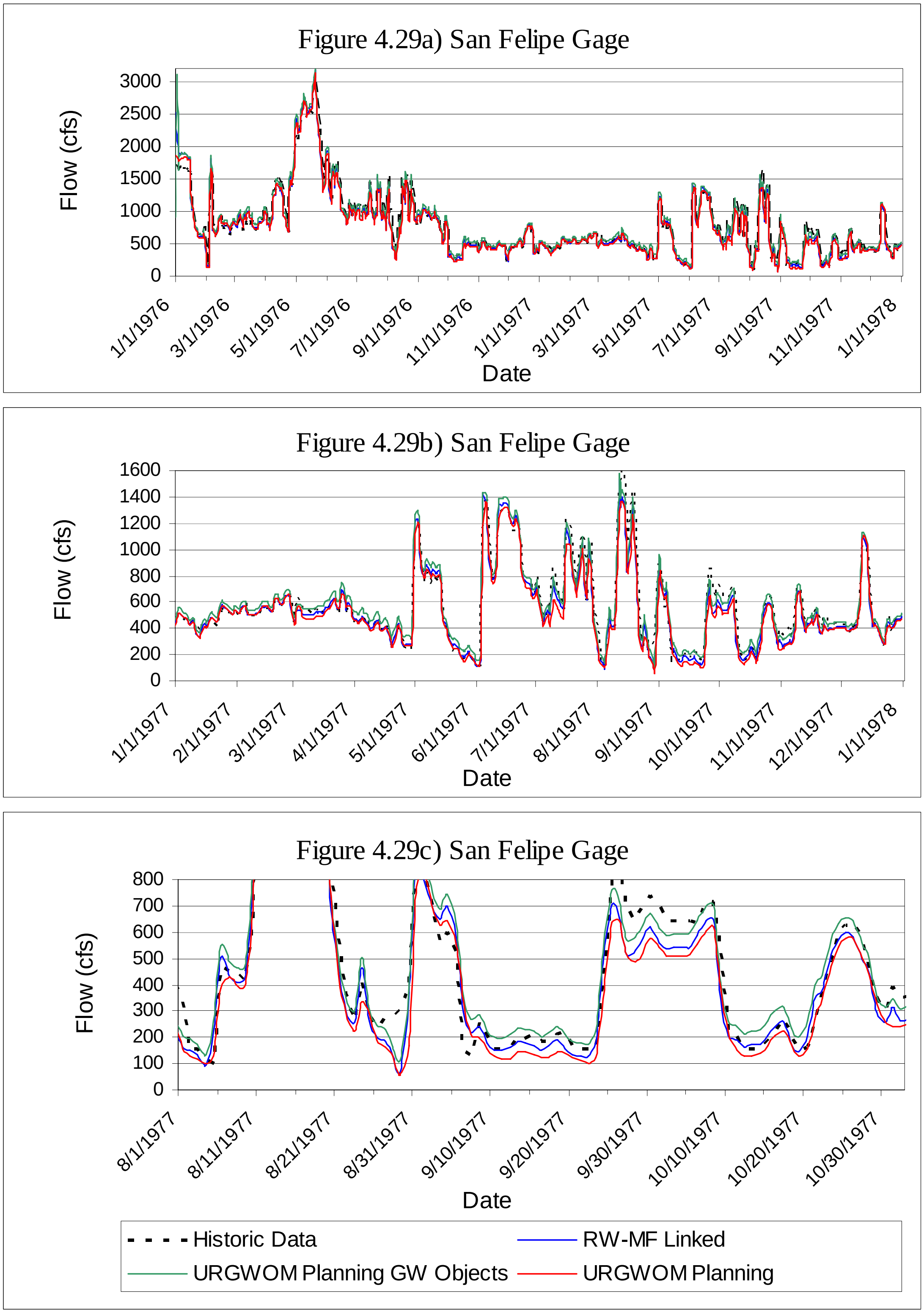
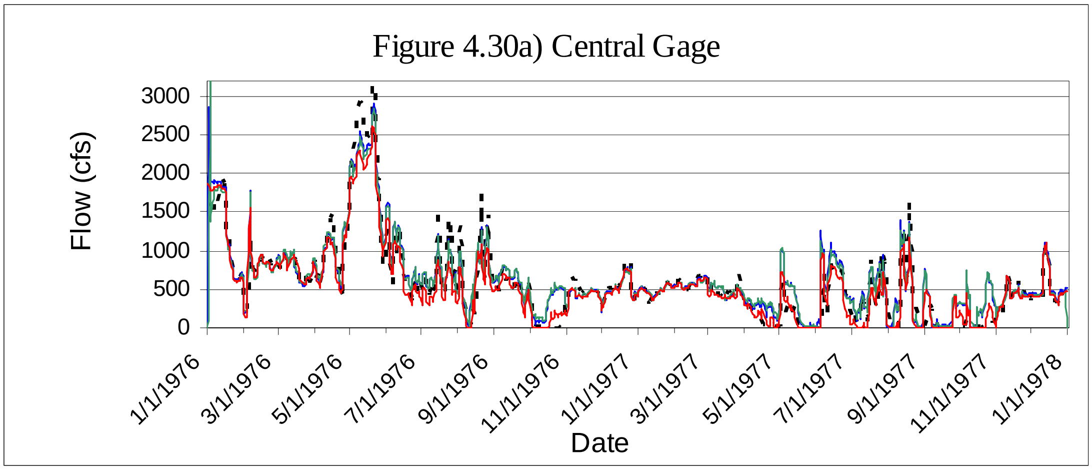
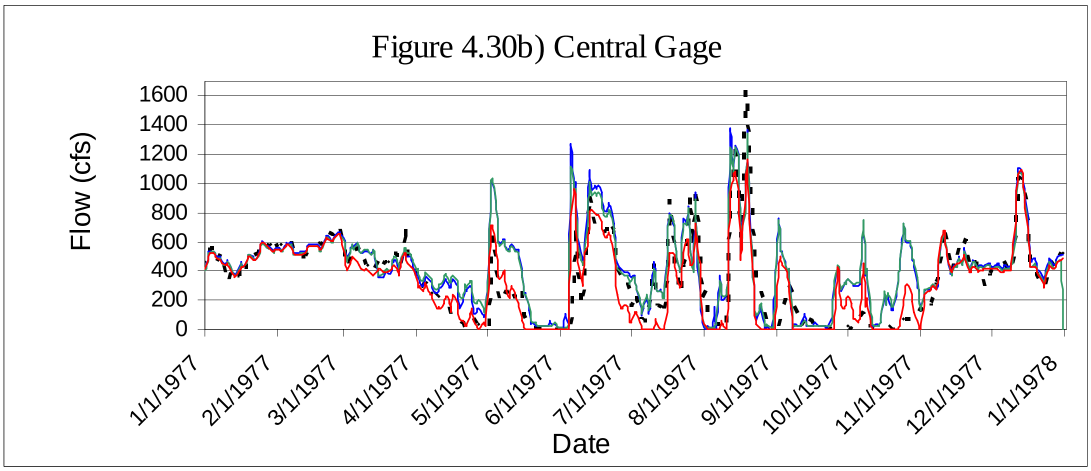


Figure 4.30) Flow at Central Gage in Cochiti to Central Models 1976-1977.





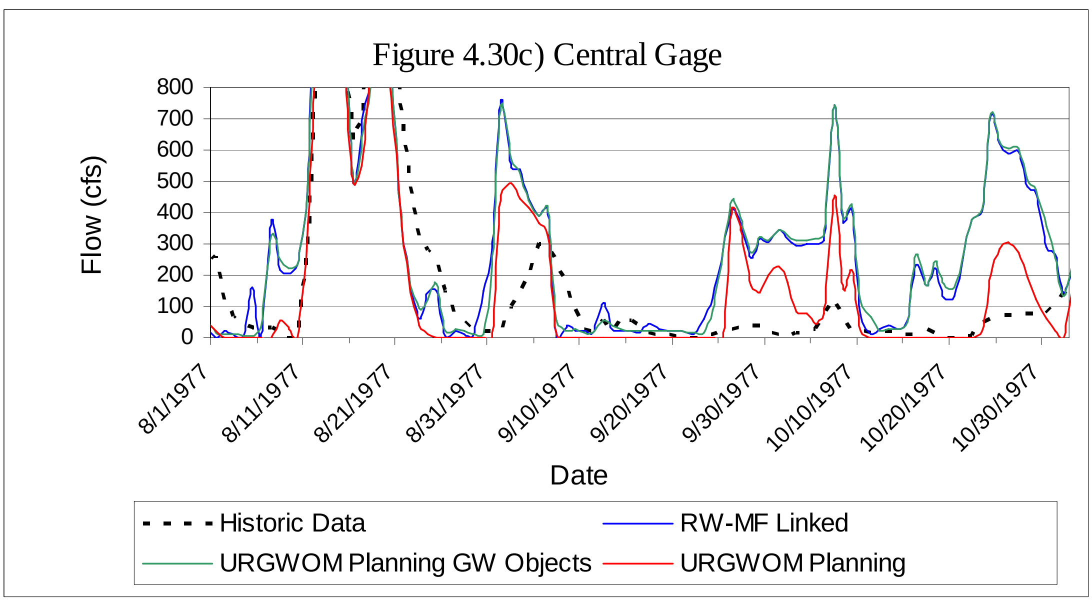
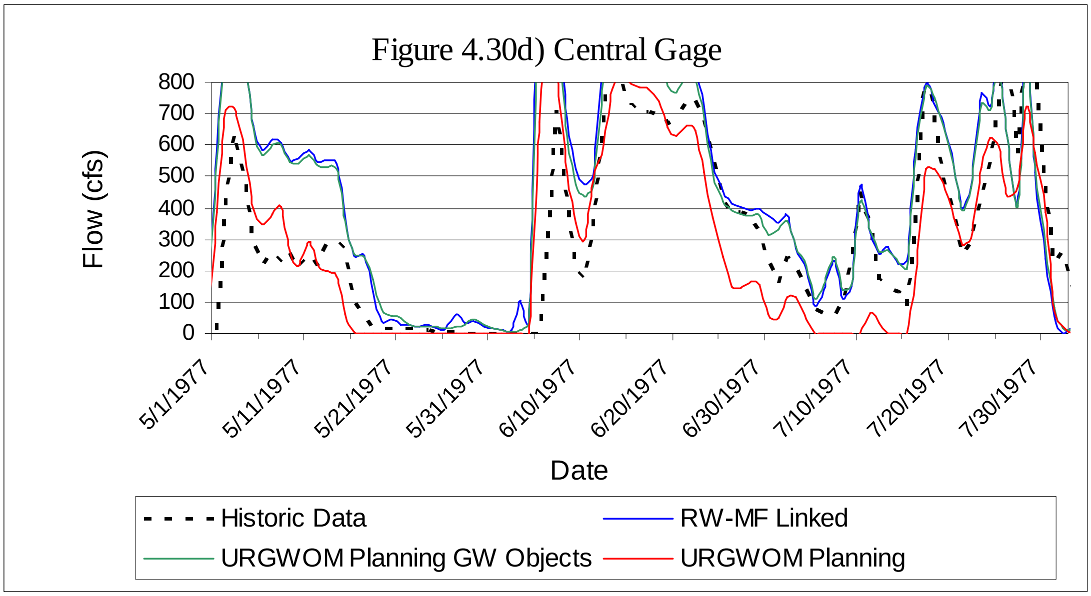


Figure 4.30 cont.) Flow at Central Gage in Cochiti to Central Models 1976-1977.



4.5 Case Study 4: Investigation of Low Flow Sensitivity

This fourth case study applies two different low inflow scenarios to the RW-MF Linked, URGWOM Planning GW Objects, and URGWOM Planning models of the Cochiti to Central region and compares their results. First, model outputs for an artificial low flow situation are compared, and second, model inflows necessary to meet a downstream low flow target and the resulting model outputs are compared.

4.5.1 Scenario 1 – Artificial Low Flow Scenario

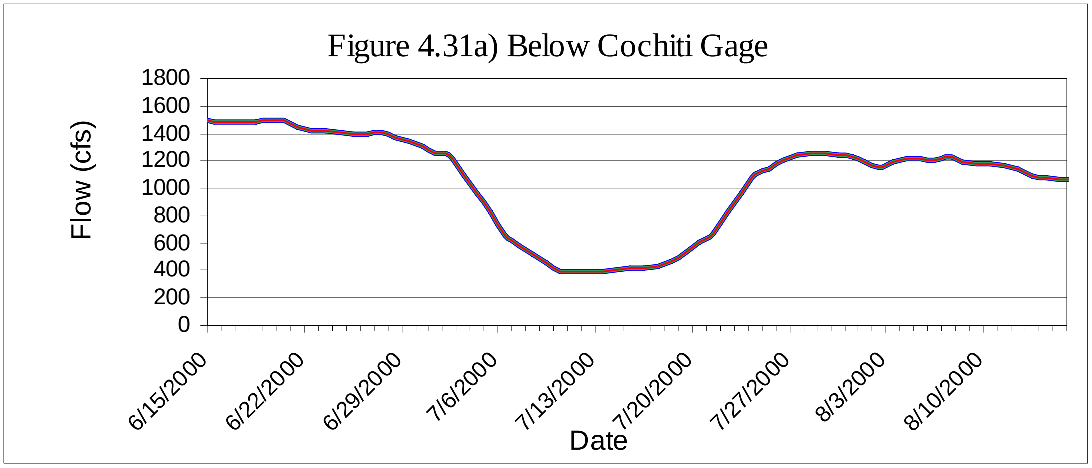
The URGWOM Planning model 1999-2000 provided by USACE contained a river inflow hydrograph for 1999-2000 with artificial low flows during July 2000. This hydrograph was created to mimic extreme low flow conditions that would lead to flows at the Central gage that were near or less than 100 cfs in the URGWOM Planning model. River inflows from July 3 through July 23 were decreased by between 143 and 898 cfs. As a measure of the sensitivity of the models to low flow conditions, the URGWOM Planning 1999-2000, URGWOM Planning GW Objects 1999-2000, and RW-MF Linked 1999-2000 models were run using these artificially low inflows. All model inputs, except the river inflow (set in the CochitiOutflowData object using the artificially lowered flows), remain unchanged from the descriptions provided in the model description section for 1999-2000 model runs.

Figure 4.31 displays plots of flow at the four gages in the models, and Figures 4.32 and 4.33 present plots of the calculated river/aquifer gain/loss (seepage). The period of artificially lowered inflows is apparent for all three models in the plots of the gages located in the main river channel. All three models display a similar trend in flow reduction between July 3 through July 23. All three models produce the same flow at the Below Cochiti gage, and river flows produced at the Cochiti Canal at San Felipe gage are identical for the URGWOM Planning GW Objects and RW-MF Linked models. At the San Felipe and Central gages, a minimal difference is observed in the flows produced by the URGWOM Planning GW Objects and RW-MF Linked models (Figure 4.31c and 4.31d). Both of these models, predict greater flows at these downstream gages than the URGWOM Planning model and a large difference of approximately 300 cfs is noted during the period of lowered flow at Central (Figure 4.31d).

As discussed in Case Study 3, the direction of the calculated net seepage flux in the Upper portion of the URGWOM Planning model is opposite to the direction of net flux calculated in the URGWOM Planning GW Objects and RW-MF Linked models (Figure 4.33a), and overall the calculated seepage in URGWOM Planning model is greater than in the other two models. Between the URGWOM Planning GW

Objects model and the RW-MF Linked model, seepage in the URGWOM Planning GW Objects model appears to be the most sensitive to reduced river inflows, especially in the lower portion of the river as can be seen in Figures 4.32e, 4.32f, and 4.33b. In these plots the observed change in calculated seepage, at the beginning and end of the low flow period, is more drastic in the URGWOM Planning GW Objects model than either of the other two models. The estimated differences between the URGWOM Planning GW Objects model and the RW-MF Linked model may be attributed to differences in conductance, area, initial storage, and initial elevation set on the RiverWare **GroundWater** objects in both models and on the conductances and initial elevations set in the MODFLOW portion of the RW-MF Linked model. As described in the model description section, little effort was made to calibrate the RW-MF Linked model and adjustment of these parameters could increase/decrease the models sensitivity to changes in river flow.

Figure 4.31) Flow at Gages in Cochiti to Central Models for Artificial Low Flow Scenario. In Figure a, all the three models have identical flow. In Figure b, the RW-MF Linked and URGWOM Planning GW Objects models have identical flow.



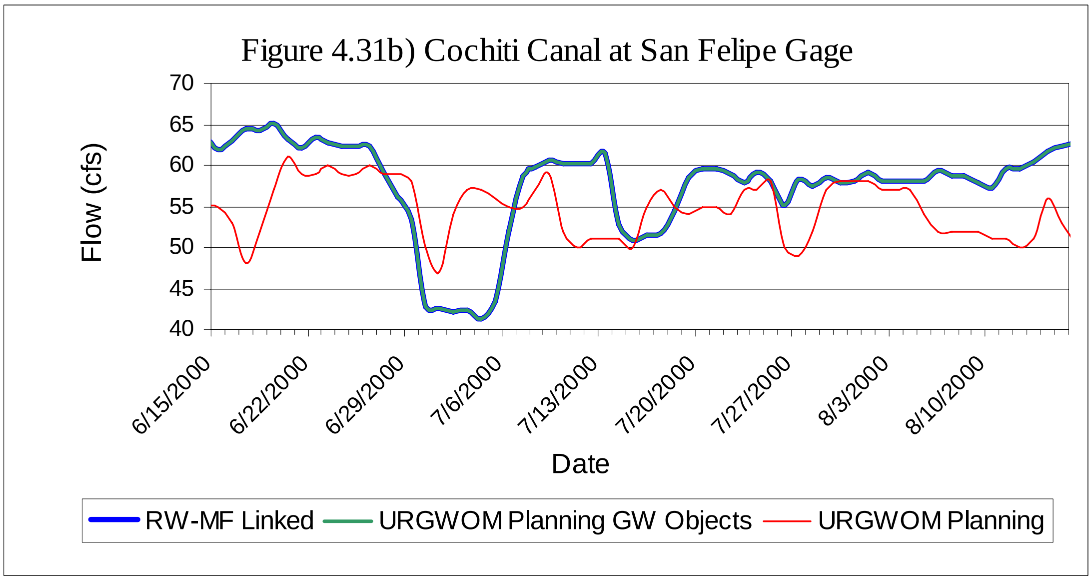
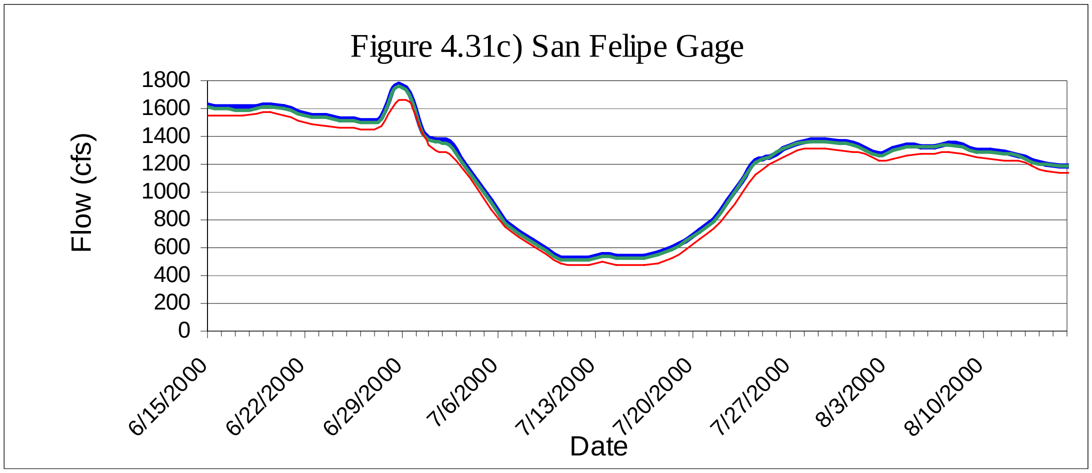


Figure 4.31 cont.) Flow at Gages in Cochiti to Central Models for Artificial Low Flow Scenario.



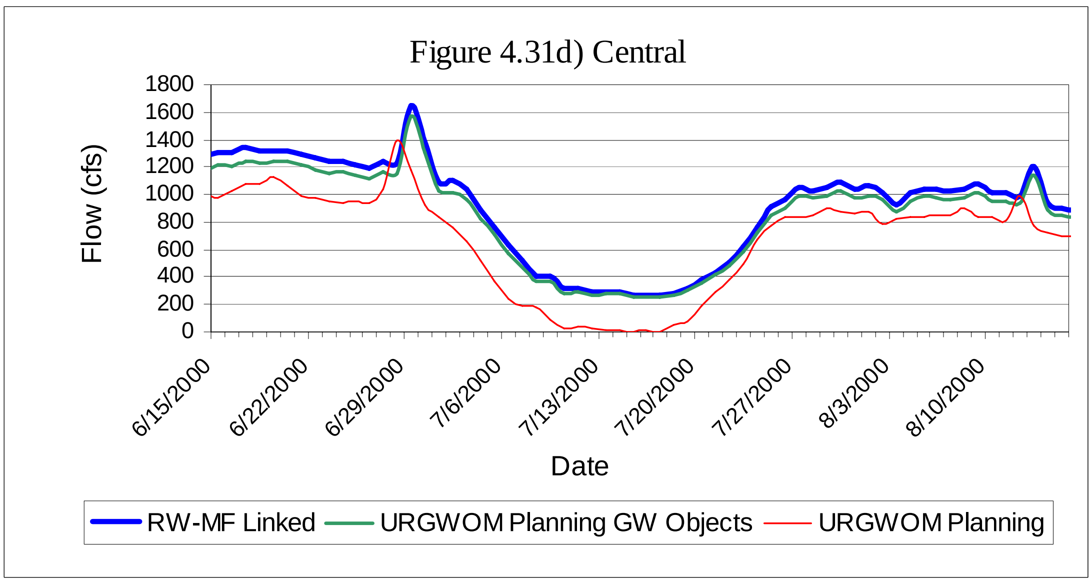
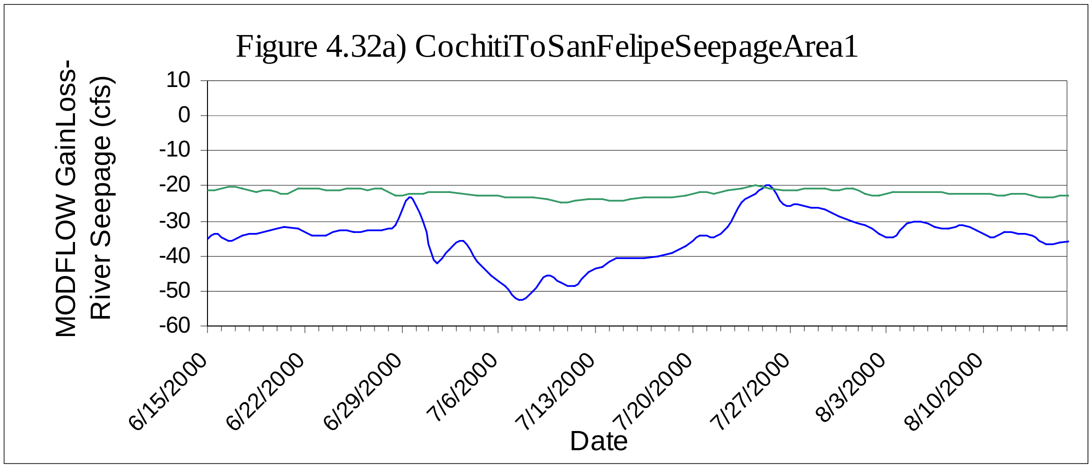
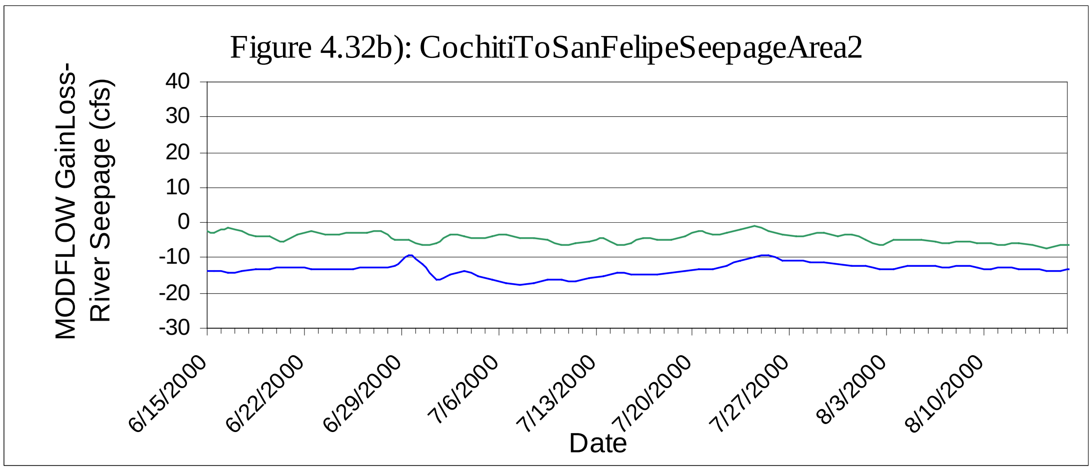


Figure 4.32) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Artificial Low Flow Scenario. River Seepage is displayed by RiverWare object.





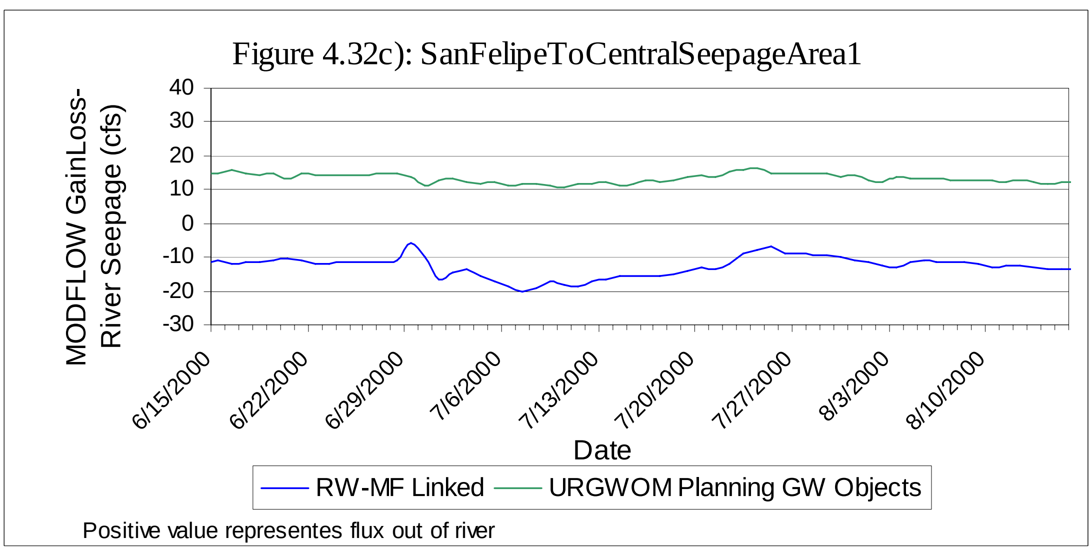
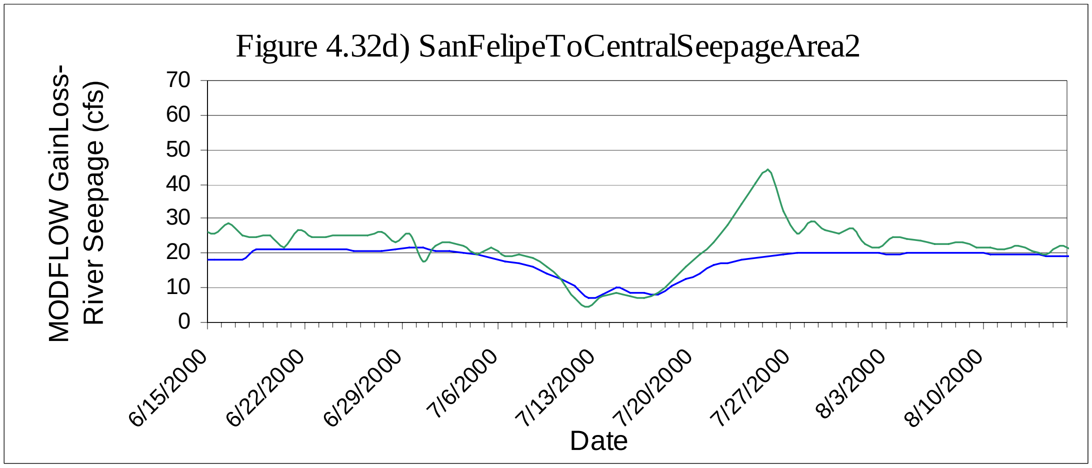
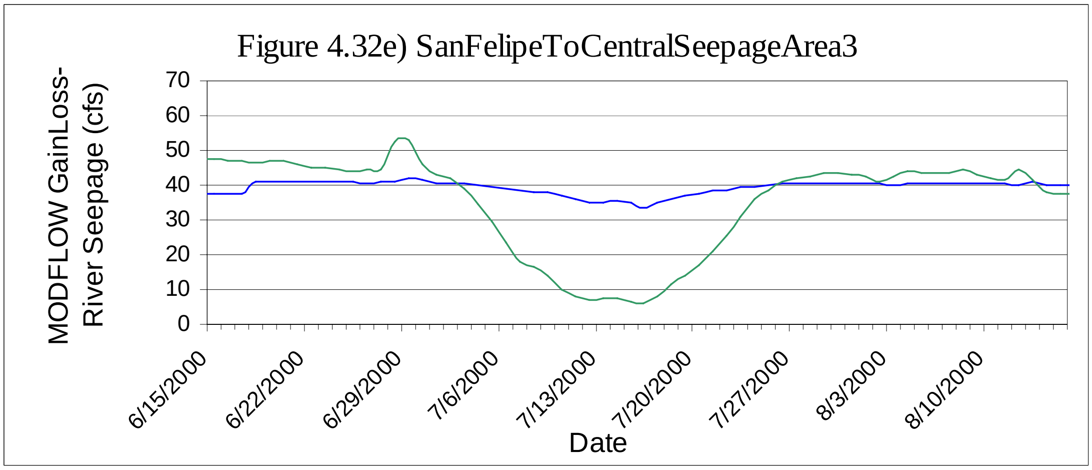


Figure 4.32 cont.) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Artificial Low Flow Scenario. River Seepage is displayed by RiverWare object.





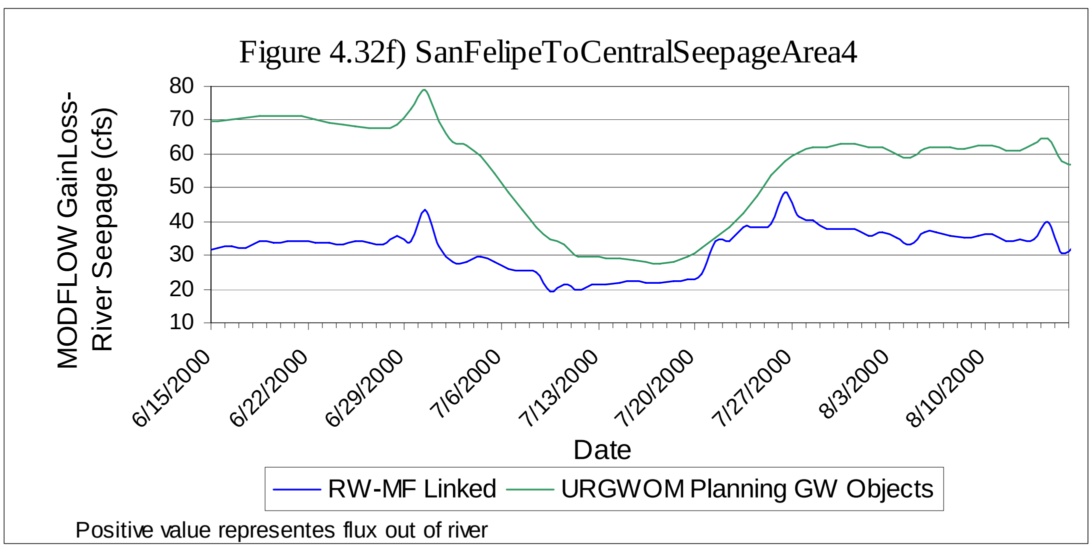
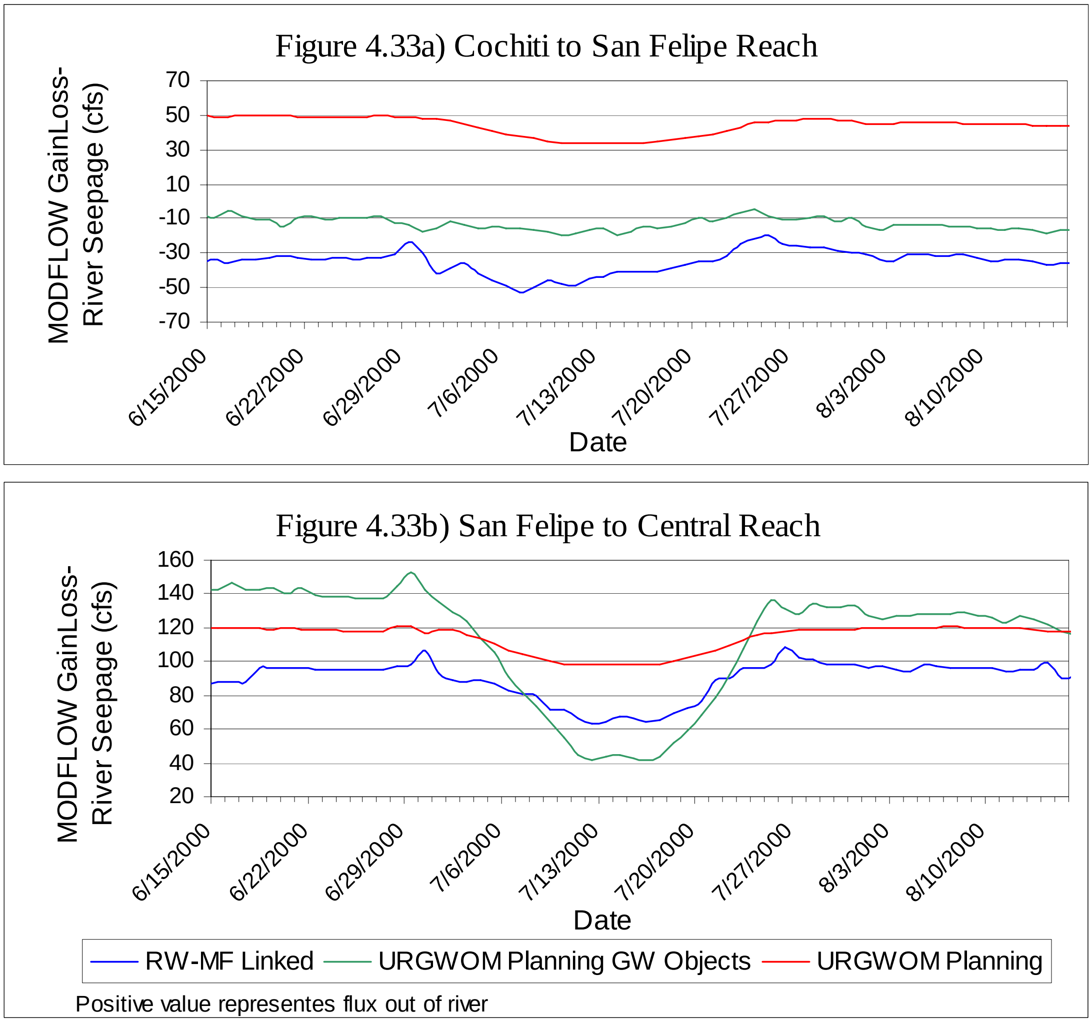


Figure 4.33) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Artificial Low Flow Scenario. Total River Seepage is displayed over each reach Cochiti and Upper Albuquerque.



4.5.2 Scenario 2 – Upstream Release Variation to Meet Downstream Low Flow Target

For this second scenario the URGWOM Planning 1999-2000, URGWOM Planning GW Objects 1999-2000, and the RW-MF Linked 1999-2000 models were run with adjusted upstream river inflow values. Since a goal of the RiverWare-MODFLOW link is to better predict downstream flows based on upstream releases, the river inflow values set in the CochitiOutflowData object (Figures 4.14 to 4.16) were adjusted in each model, from July 10, 2000 through July 22, 2007, so that a low flow target of roughly100 cfs was met at the Central gage at the base of the models. CochitiOutflows or releases were considered acceptable when flow at the Central target was between 100 and 100.5 cfs.

Figure 4.34 displays plots of the release/river inflows set in the CochitiOutflowData object and the flows produced at the San Felipe and Central gages. From Figure 4.34 it is apparent that a much greater release is necessary to meet the 100 cfs target at Central in the URGWOM Planning model than in the other two models. Table 4.6 displays the release values (CochitiOutflow), target flow at the Central gage, and the total volume of gage inflow and seepage gain/losses over the target flow period. The calculated cumulative release necessary to meet the target from July 13 to July 22 is 1918.49 acre-feet (RW-MF Linked), 2082.37 acre-feet (URGWOM Planning GW Objects), and 3537.28 acre-feet (URGWOM Planning), with total target volumes recorded at the Central gage for the same period of 504.46, 505.38, and 505.51 acre-feet, respectively. Essentially, over this time period, in the URGWOM Planning model, the released volume of water necessary to consistently meet the target at Central (3537.28 acre-feet) is almost double the amount needed in the RW-MF Linked model (1918.49 acre-feet). One reason that more water must be released in the URGWOM Planning model is that in this model the river loses a significantly greater amount of water to the aquifer than in the RW-MF Linked model. In fact, over the 10 day period the river loses roughly 692.40 acre-feet to the aquifer in the URGWOM Planning model and in the RW-MF Linked model it gains

109.86 acre-feet (Table 4.6). As stated in the previous section, the regression equation used to calculate river leakage in the URGWOM Planning model can only calculate river losses and not gains. The differences in river seepage alone however, do not account for the entire difference in release estimates between the two models. They account for approximately half of the released volume difference; therefore it can be stated that while the calculated seepage has a strong influence on the amount of water that needs to be released in order to meet the target flow, other factors contribute to the observed flow differences between the two models and have just as great an influence as seepage (see Section 4.5.3 for a detailed description of these differences).

As far as the RW-MF Linked model and the URGWOM Planning GW Objects models are concerned, the observed differences in calculated flow at the gages and river gain/loss estimates are much less between these models than when compared with URGWOM Planning model. A net gain to the river from the aquifer is calculated by the RW-MF Linked model (109.86 acre-feet) over the 10 day period, while a net loss is calculated by the URGWOM Planning GW Objects model (5.05 acre-feet). The remaining difference in the released volume may be attributed to calculated drain return flows. The drain return flows to the main river channel are greater in the RW-MF Linked model; thus a lower flow release is able to meet the target. The difference in drain return flow arises from the difference in configuration between the drains in the two models. In the RW-MF Linked model, flow through the drains is represented in the MODFLOW portion of the model instead of in RiverWare.

Figure 4.34) Flow at Gages in Cochiti to Central Models for Target Flow Scenario.

Figure 4.34a) Cochiti Outflow

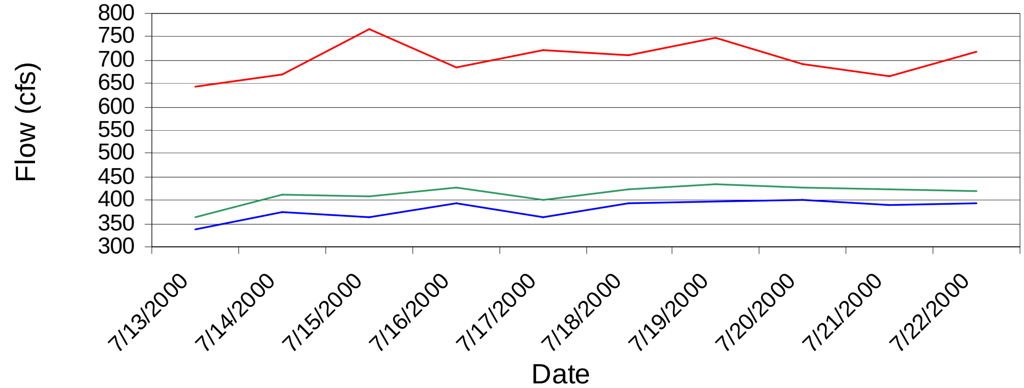


Figure 4.34b) San Felipe Gage

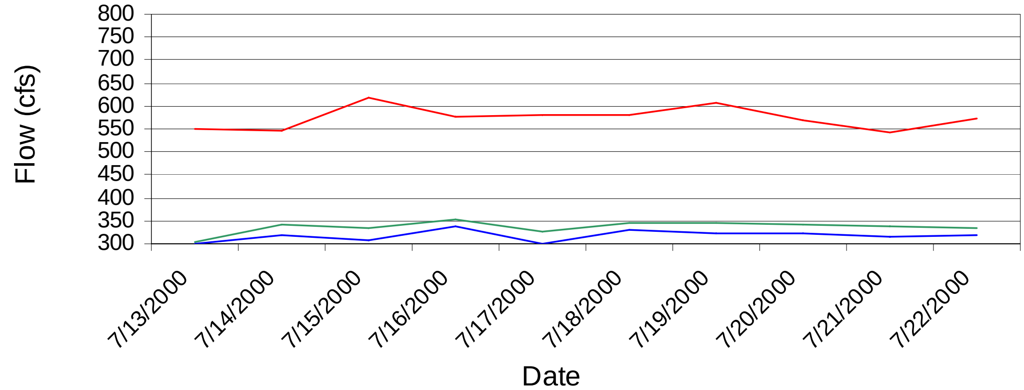


Figure 4.34c) Central Gage

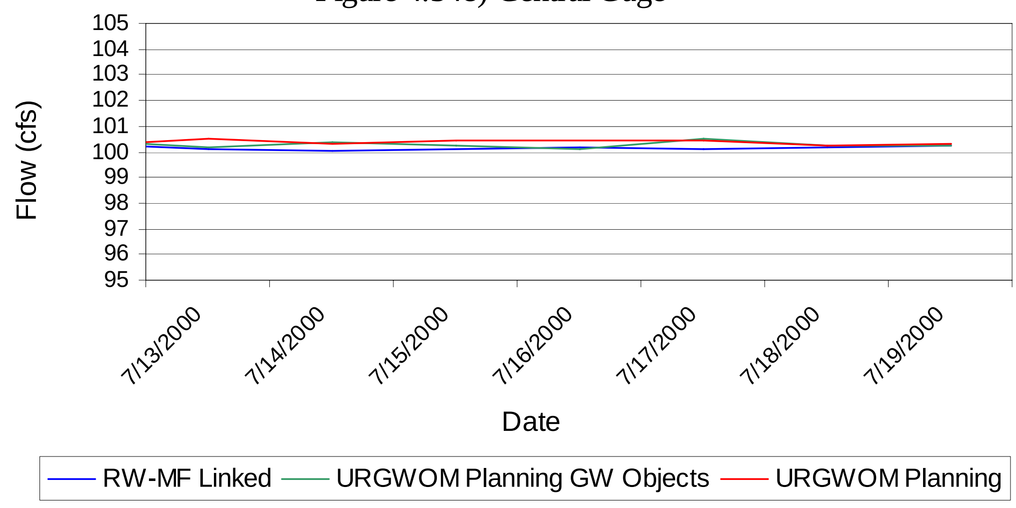


Figure 4.35) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Target Flow Scenario. River Seepage is displayed by RiverWare object.

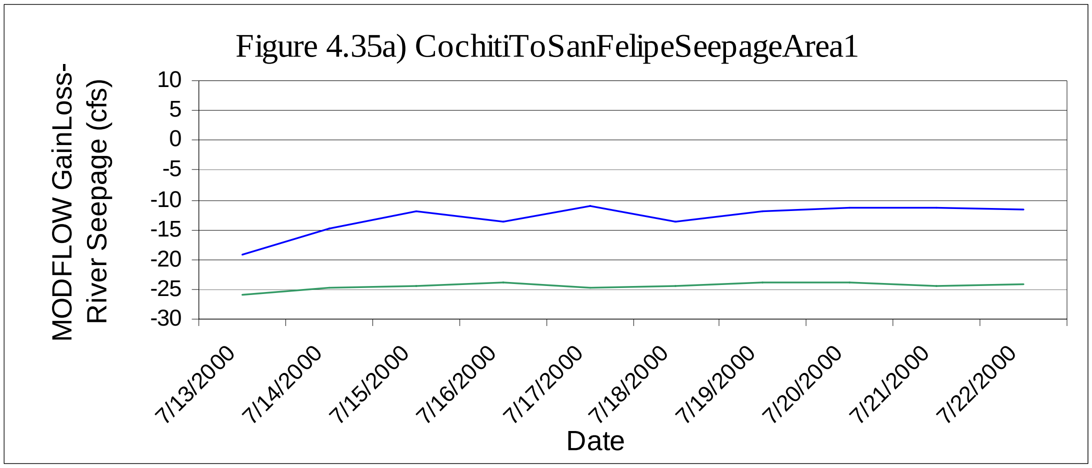


Figure 4.35a) CochitiToSanFelipeSeepageArea1

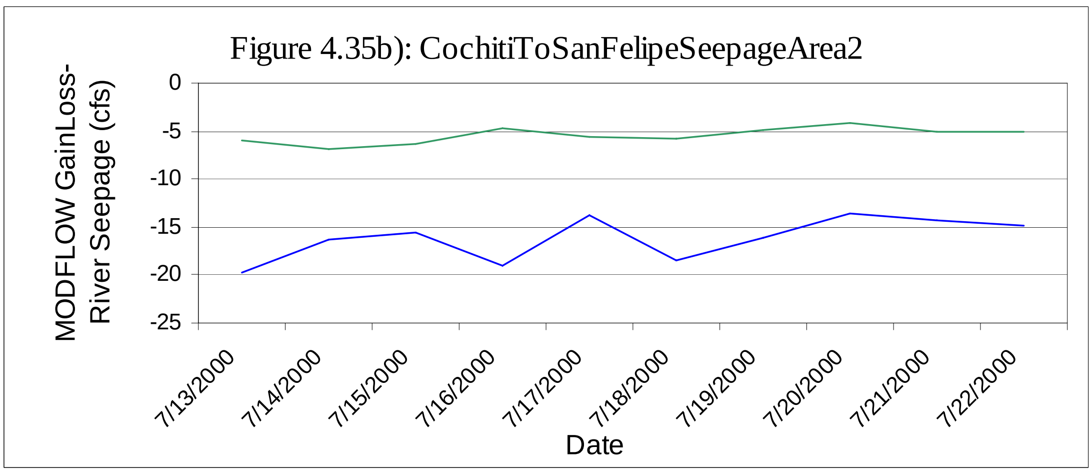


Figure 4.35b): CochitiToSanFelipeSeepageArea2

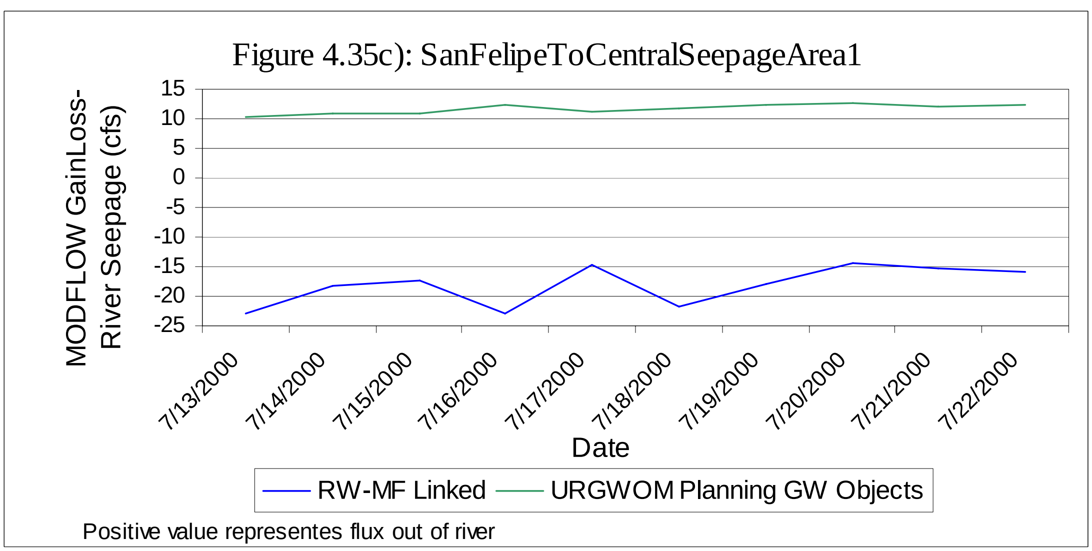
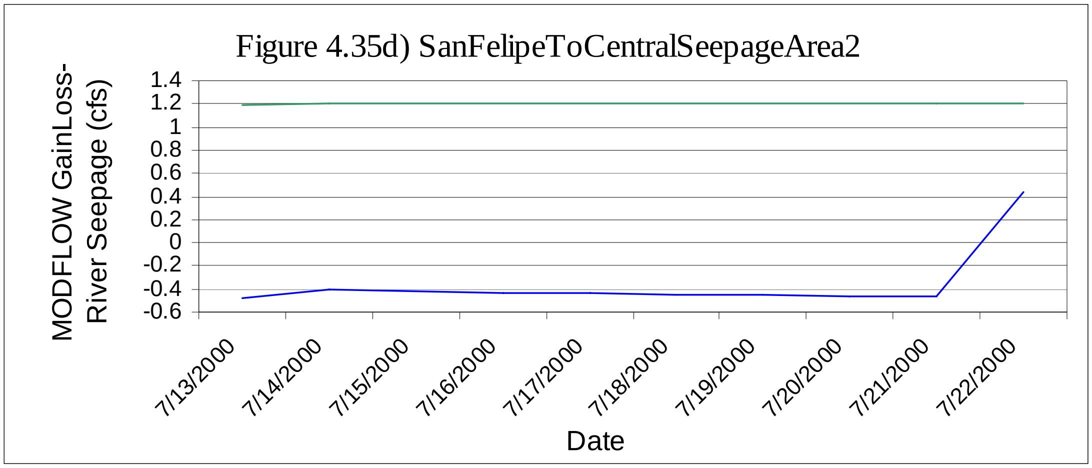
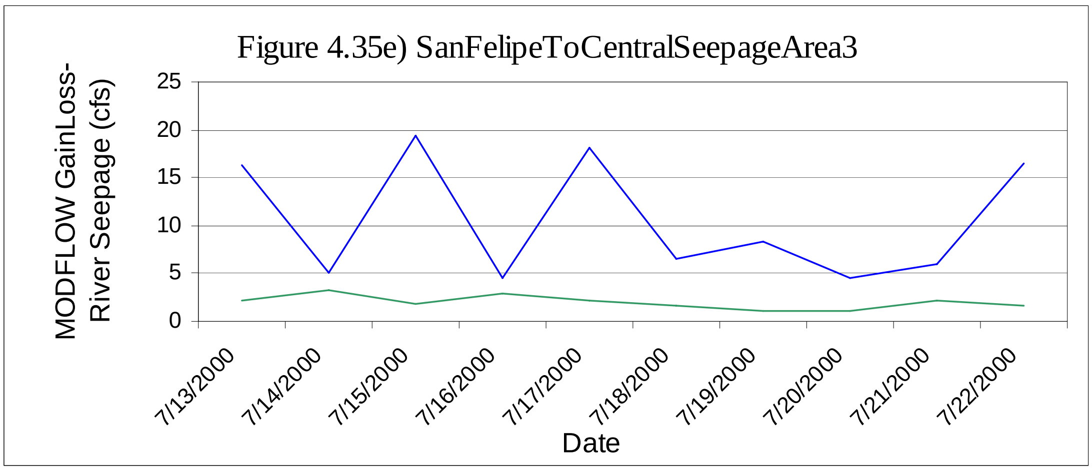


Figure 4.35c): SanFelipeToCentralSeepageArea1

Figure 4.35 cont.) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Target Flow Scenario. River Seepage is displayed by RiverWare object.





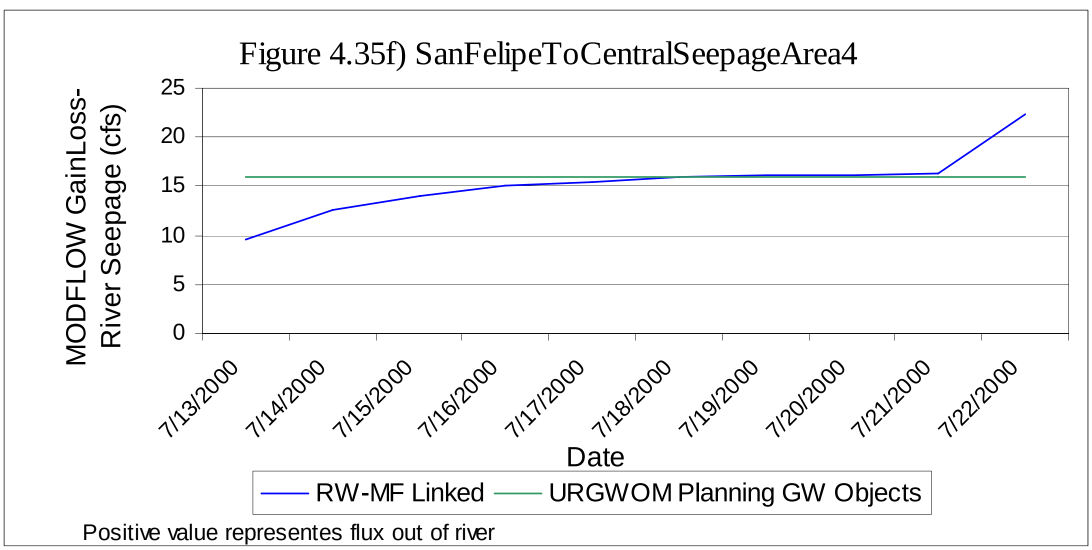


Figure 4.36) River Seepage/MODFLOW GainLoss for the Cochiti to Central Models Target Flow Scenario. River Seepage is displayed for Upper and Lower sections in the model.

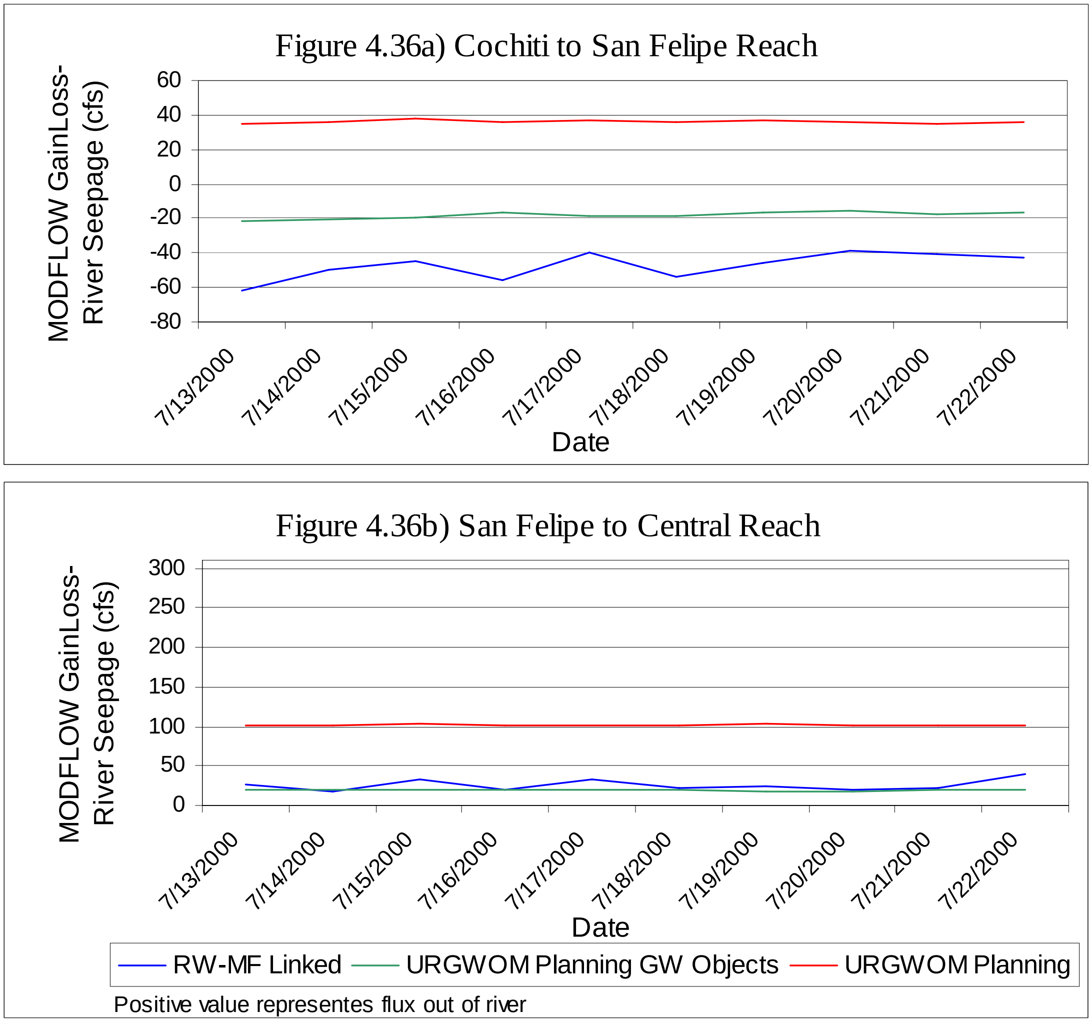


Table 4.6) Cochiti to Central Models Target Flow Scenario Data Table. Individual cell or reach and total volume values over the ten day, July 13 through July 22 test, are provided for CochitiOutflow, Central Gage flow, and river GainLoss/seepage.

Object	CochitiOutflow			San Felipe Gage			Central Gage		
Value	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
Model	RW-MF Linked	URGWOM Planning GW Objects	URGWOM Planning	RW-MF Linked	URGWOM Planning GW Objects	URGWOM Planning	RW-MF Linked	URGWOM Planning GW Objects	URGWOM Planning
7/10/2000	340.00	420.00	568.00	258.43	344.36	645.10	931.14	923.50	211.36
7/11/2000	411.00	446.00	695.00	380.50	369.71	541.19	127.75	100.72	117.38
7/12/2000	301.00	375.50	697.00	233.61	288.65	570.09	100.01	100.31	100.30
7/13/2000	337.10	362.00	643.00	299.20	302.31	551.44	100.06	100.40	100.30
7/14/2000	373.00	411.00	670.50	320.69	339.88	545.14	100.11	100.46	100.19
7/15/2000	363.00	409.00	767.00	306.84	335.12	617.73	100.30	100.47	100.27
7/16/2000	393.00	426.50	686.00	338.09	351.69	574.72	100.10	100.19	100.48
7/17/2000	364.50	399.50	723.00	301.08	327.00	579.18	100.06	100.39	100.29
7/18/2000	395.10	423.00	709.00	331.98	345.22	580.30	100.07	100.24	100.47
7/19/2000	398.50	433.50	749.50	321.24	346.40	606.55	100.14	100.09	100.45
7/20/2000	401.50	427.50	690.00	324.02	341.45	569.88	100.09	100.48	100.46
7/21/2000	390.00	422.00	666.50	315.48	337.69	541.51	100.20	100.21	100.23
7/22/2000	392.50	419.50	717.00	318.73	333.90	571.76	100.22	100.24	100.31
Total Volume July 13 through July 22 (acre-ft)	1918.49	2082.37	3537.28				504.46	505.38	505.51
Model	**RW-MF Linked**			**URGWOM Planning GW Objects**			**URGWOM Planning**		
Reach	Cochiti	Upper Albuquerque		Cochiti	Upper Albuquerque		Cochiti	Upper Albuquerque	
Volume of River GainLoss by Reach July 13 through July 22 (acre-ft)	-238.46	128.60		-91.73	96.78		181.46	510.94	
Total Volume of River GainLoss July 13 through July 22 (acre-ft)	-109.86			5.05			692.40		

4.5.3 Investigation into Model Water Balance Differences: URGWOM Planning and URGWOM Planning GW Objects

In both low flow scenarios, a large discrepancy was noted in river flow between the URGWOM Planning model and the other two models (RW-MF Linked and URGWOM Planning GW Objects). In Scenario 1, large differences were observed in the amount of flow modeled at the Central gage, and in Scenario 2 a large difference was noted in the amount of flow released to meet the target at the Central gage. Essentially, the URGWOM Planning model requires a larger amount of water to be released in order to produce flows similar to those in the other two models at Central. From Scenario 2, it was concluded that some of the differences in modeled flow are attributed to factors other than seepage; therefore this investigation was undertaken to identify the additional factors responsible for the differences. This exercise is meant to track differences in water movement between the URGWOM Planning model and the other two models; therefore, for the sake of simplicity this investigation compares the URGWOM Planning model to the URGWOM Planning GW Objects model only, and no references are made to the RW-MF Linked model.

To identify where differences between the two models (URGWOM Planning and URGWOM Planning GW Objects) occur, a constant release (inflow on the CochitiOutflowData object) of 700 cfs was set for July 2000 in the URGWOM Planning 1999-2000 model and the URGWOM Planning GW Objects 1999-2000 model. The model simulations were run for the full 2 year period but the results are discussed for July 2000 only. Figure 4.37 shows an overall water balance for the region. River inflow to the region is identical in both models and is shown in

Figure 4.37 as dotted lines. Modeled outflow from the region is shown as solid lines in Figure 4.37, where outflow is the sum of the river and canal outflows at the base of the region. It obvious that more water is consumed/lost over the region by the URGWOM Planning model than by the URGWOM Planning GW Objects model. In fact a 29 percent difference in total volume of water exiting the modeled region (via the river and the canals) over the month of July was found (Table 4.7). To get an initial idea of where the model's water balances diverge, flows at the four gages are compared (Figure 4.38). Figure 4.38 displays the modeled flow at the Cochiti Canal at San Felipe gage, San Felipe gage and Central gage and Table 4.7 provides the total volume of water that passes each gage as well as the mean daily flow rate at each gage for the month of July 2000. Modeled flows at the gage below Cochiti were identical and are not shown. As described in the two low flow Scenarios, slight flow differences are noted at the Cochiti Canal at San Felipe gage. These differences (approximately 1 cfs) are minimal when compared with the flow differences observed at the San Felipe gage (approximately 44 cfs) and Central gage (approximately 243 cfs) (Table 4.7). It is apparent that the largest discrepancy occurs in the Lower region of the model between San Felipe and Central.

Figure 4.37) Water Balance for Cochiti to Central Models - Water Balance Investigation.

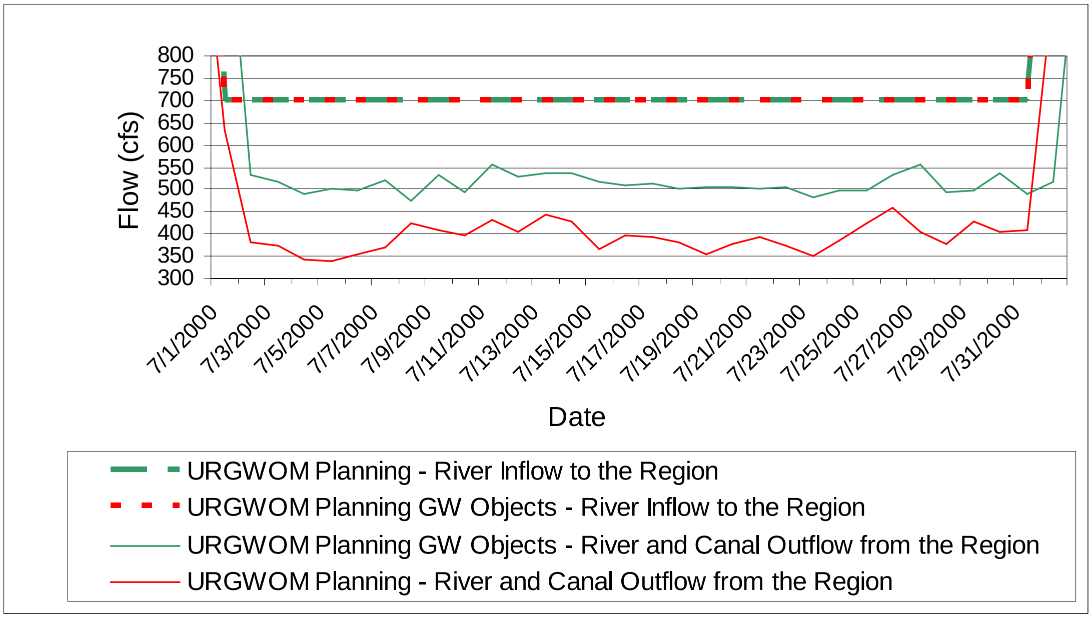
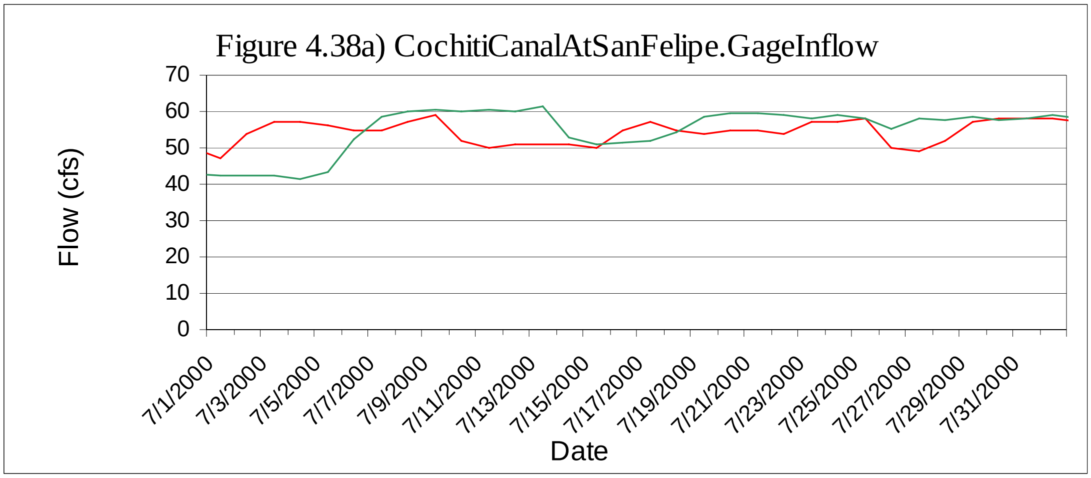
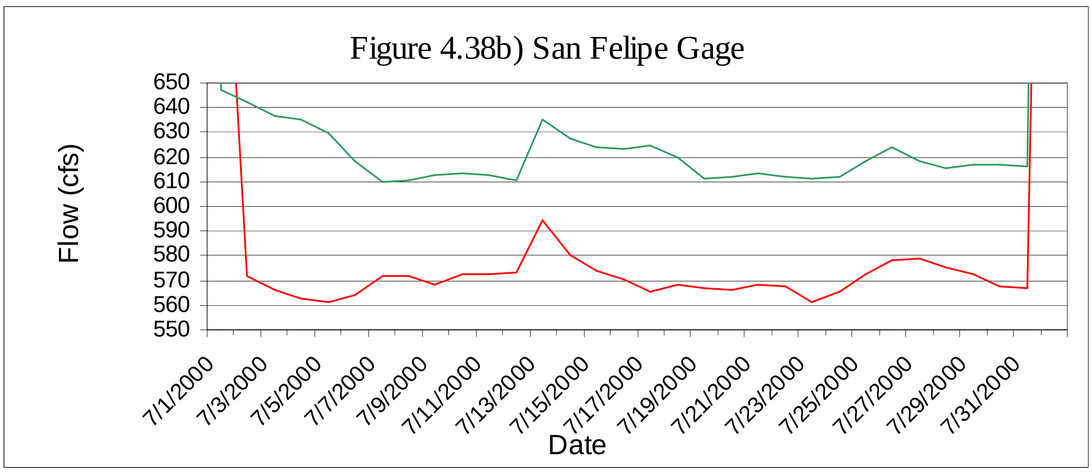


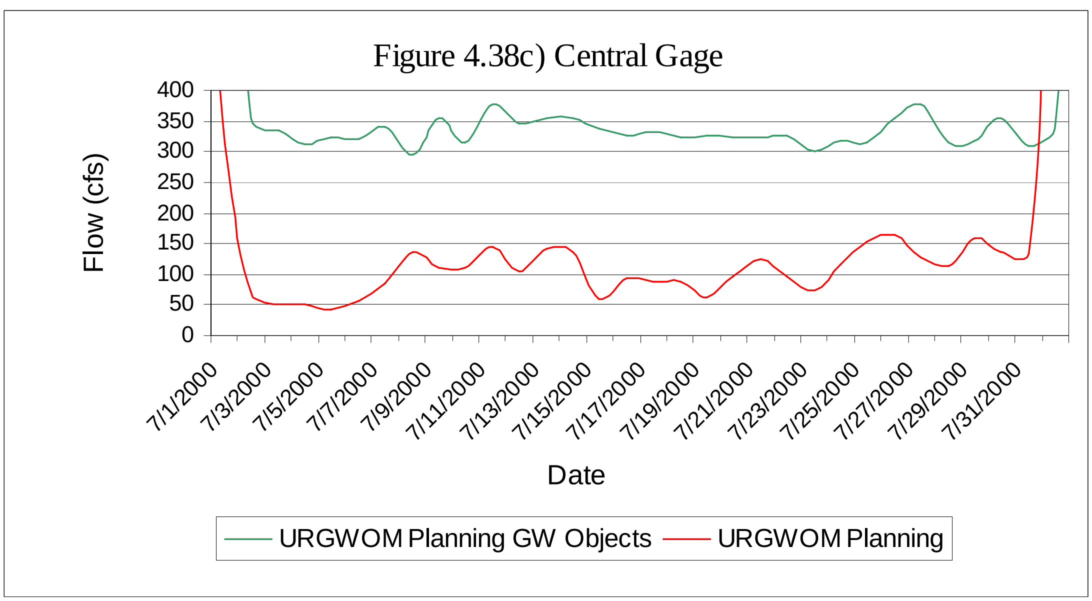
Table 4.7) Water Balance Investigation Table. The total monthly water volume and the mean daily flows for the constant release in the month of July 2000 are shown in the table below for the URGWOM Planning GW Objects Model and the URGWOM Planning Model

	Cochiti Canal at San Felipe Gage	San Felipe Gage	Central Gage	Diversions to Lower Region Canals	Canal Inflow at the Top of the Lower Region	Canal Losses to Groundwater in Lower Region	Canal Water Consumed by Irrigation in Lower Region	Flow Retruned to Main Stem of River from Lower Region Canals	Flow Remaining in Lower Region Canals at the Base of the Models	Total Flow at the Base of the Model (Flow in the Canals plus flow in the Main Stem of the River)
Total Monthly Water Volumes (acre-feet)										
URGWOM Planning GW Objects Model	3379	38154	21802	27257	30636	1207	4364	13996	11069	32871
URGWOM Planning Model	3339	35460	6831	23745	28837	2625	7061	1367	17784	24615
Percent Difference Between the two Models	1	7	105	14	6	74	47	164	47	29
Mean Daily Flows (cfs)										
URGWOM Planning GW Objects	55	620	355	443	498	20	71	228	180	535
URGWOM Planning	54	577	111	386	469	43	115	22	289	400
Mean Daily Difference Between the two Models	1	44	243	57	29	-23	-44	205	-109	134

Figure 4.38) Flow at Gages Cochiti To Central Models - Water Balance Investigation.



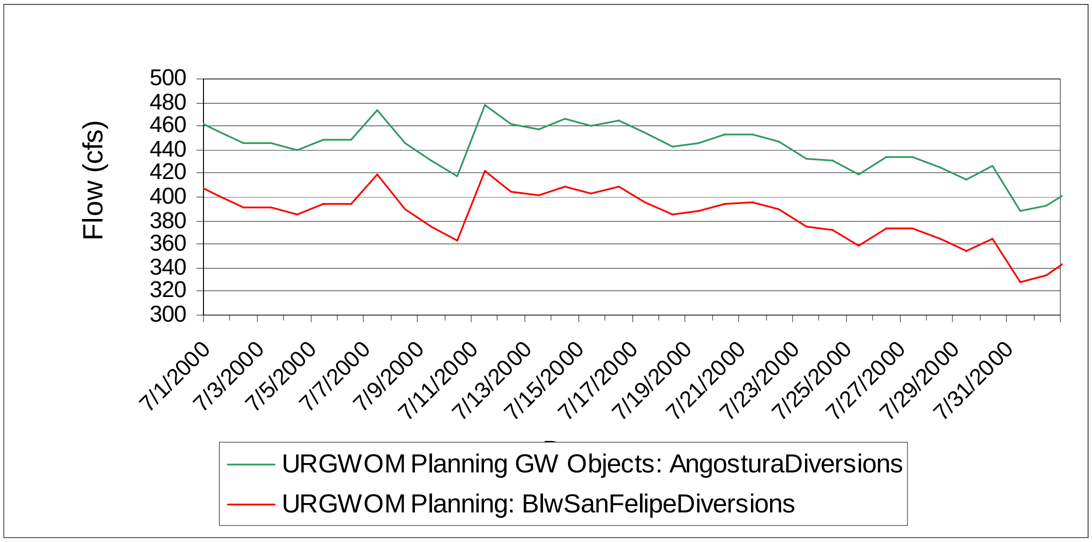




To rule out any differences due to user input variations, all confluences to and diversions from the main stem of the river were compared. Figures 4.14 and 4.15 show the locations of the objects within each model that are referenced in the discussion below. Inflows to the river from Galisteo, BlwJemez, BernalilloWastewater, RioRanchoWastewater, NorthFloodwayChannel, and AlbuquerqueWaterUser are identical in both models. Diversions to the Upper region canal(s) set by the BlwCochitiDiversions object are also identical. Diversions to the Lower region canal(s) as shown in Figure 4.39 are not identical; instead the URGWOM Planning model appears to divert less water than the URGWOM Planning GW Objects model (Table 4.7). The Aggregate Diversion Site object which handles the Lower region diversions in the URGWOM Planning model (BlwSanFelipeDiversions) contains one additional Water User (Algodones Drain), than the Aggregate Diversion Site object in the URGWOM Planning GW Objects model (Angostura Diversions). The diversions requested by the Algodones Drain are negative and thus deducted from the total diversion requests for the BlwSanFelipeDiversions object and cause the total diversion to be lower.

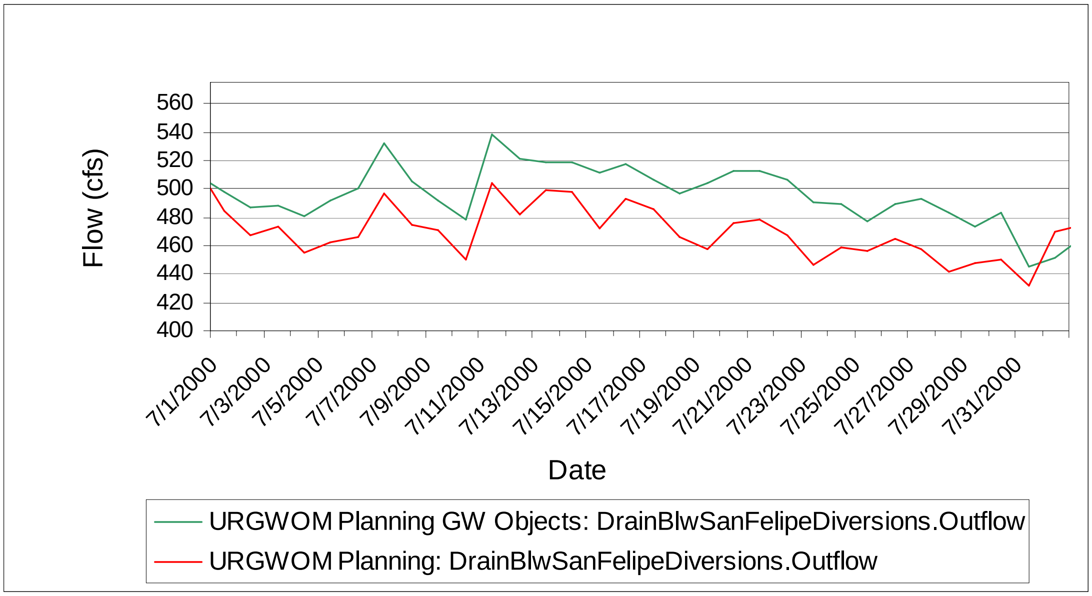
The remaining river confluences and diversions in the URGWOM Planning model not discussed above include: seepage losses (BlwCochitiToSanFelipeSeepage and BlwSanFelipeDiversions) and canal returns (CochitiBifurcation and AngosturaBifurcation). Each of these objects are represented in the Upper and Lower regions of the model. Since the modeled discrepancies were noted in the Lower portion of the model the discussion below places more emphasis on the Lower region and in particular on the differences observed in the canal flow.

Figure 4.39) Lower Region Diversions Cochiti to Central Models – Water Balance Investigation.



Canal inflows in the Lower region have three sources: 1) outflow from the Upper region canal(s); 2) set river diversions (BlwSanFelipeDiversions [URGWOM Planning model] and AngosturaDiversions [URGWOM Planning GW Objects model]); and 3) inflow from seepage (SanFlipeToCentralSeepage[URGWOM Planning model only]). The first two inflows are shown in Figures 4.38a and 4.39, respectively, and the total inflow at the top of the Lower region canal(s) is shown in Figure 4.40. This inflow is the outflow from the DrainBlwSanFelipeDiversions object (this object is present in both models). From Figure 4.40, it is obvious that canal inflow in the Lower region is lower in the URGWOM Planning model by about 29 cfs at each time-step.

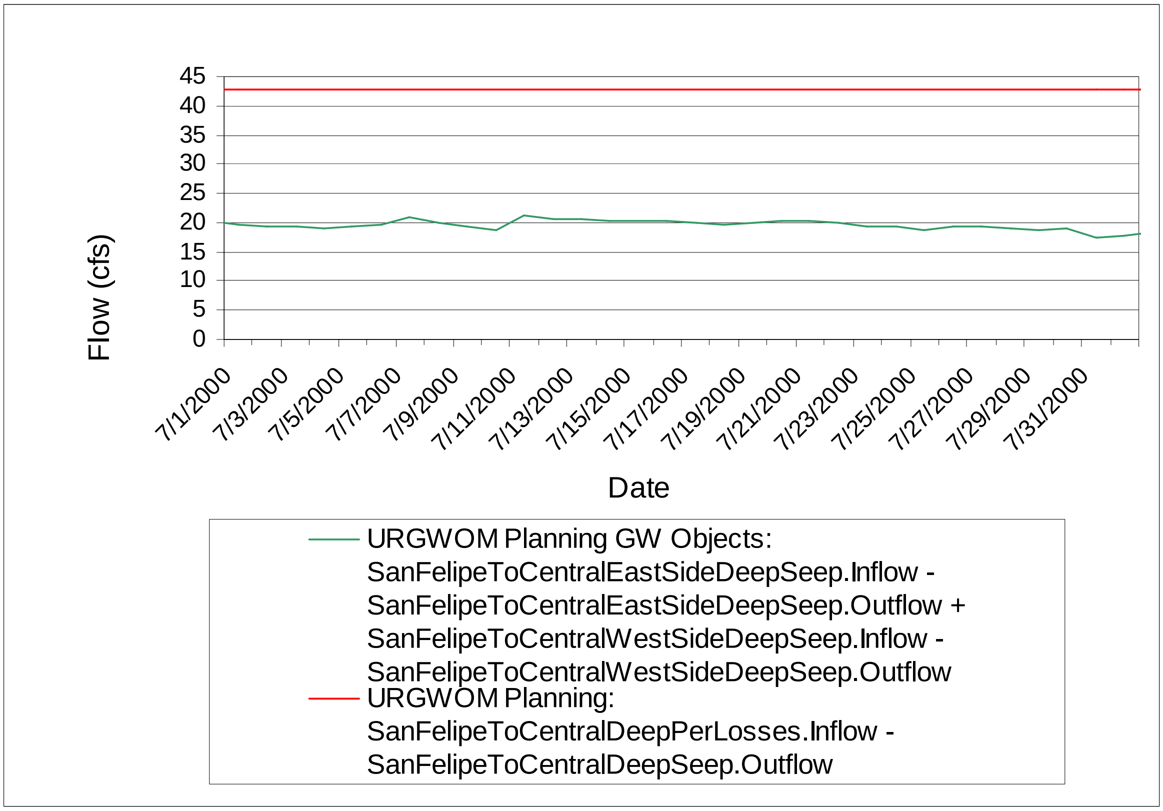
Figure 4.40) Canal Inflow at the Top of the Lower Region Cochiti to Central Models-Water Balance Investigation.



Just downstream of the DrainBlwSanFelipeDiversions object in the URGWOM Planning model, are the SanFelipeToCentralCropDeepPercLosses object and the SanFelipeToCentralCanalDeepSeep object. These objects calculate canal losses to groundwater and represent a sink in the model from which water cannot be recovered. The sum of these losses is shown in Figure 4.41. Figure 4.41 also shows the canal losses to groundwater in the URGWOM Planning GW Objects model. At this point in the URGWOM Planning GW Objects model, the canal has been broken into eastern and western parts; therefore, the canal groundwater losses in the eastern and western canals were added to obtain the total loss. In the URGWOM Planning GW Objects model, unlike in the URGWOM Planning model, the canal losses to groundwater are linked with the shallow aquifer system and do not represent a sink of unrecoverable flow. Additionally, the methods used to calculate canal losses to groundwater are not the same in the two models. Figure 4.41 and Table 4.7 show that the URGWOM Planning model produces greater canal losses (approximately

23 cfs more is lost at each time-step) to groundwater than the URGWOM Planning GW Objects model.

Figure 4.41) Lower Region: Total Flow Lost to Canal Seepage and Deep Percolation Cochiti to Central Models – Water Balance Investigation.



The modeled irrigation consumption losses are shown in Figure 4.42. A greater quantity of canal water (approximately 44 cfs more at each time-step [Table 4.7]) is consumed by irrigation in the URGWOM Planning model than the URGWOM Planning GW Objects model. Irrigation consumption is calculated by different methods in the two models. Just below the irrigation and canal groundwater losses, the amount of flow in the canals is considerably lower in the URGWOM Planning model, approximately 100 cfs, than in the URGWOM Planning GW Objects model (Figure 4.43). Thus the differences in diversions to and calculations performed on the canals are a major contributor to noted model inconsistencies.

Figure 4.42) Lower Region: Canal Water Consumed by Irrigation Cochiti to Central Models – Water Balance Investigation.

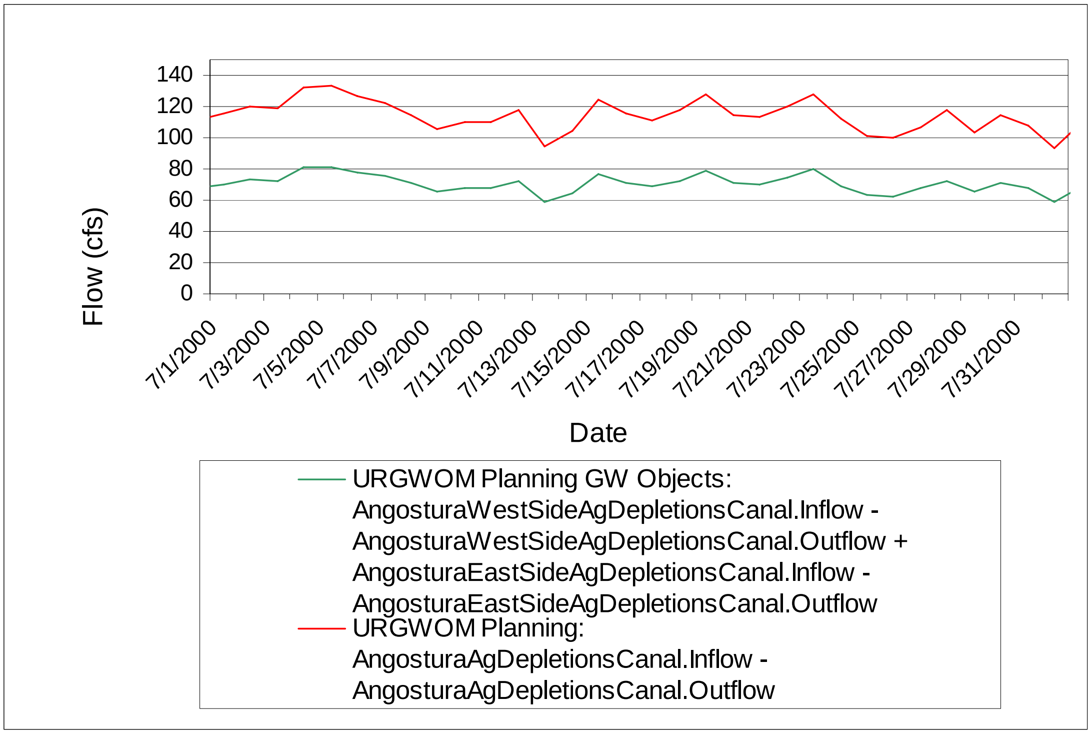
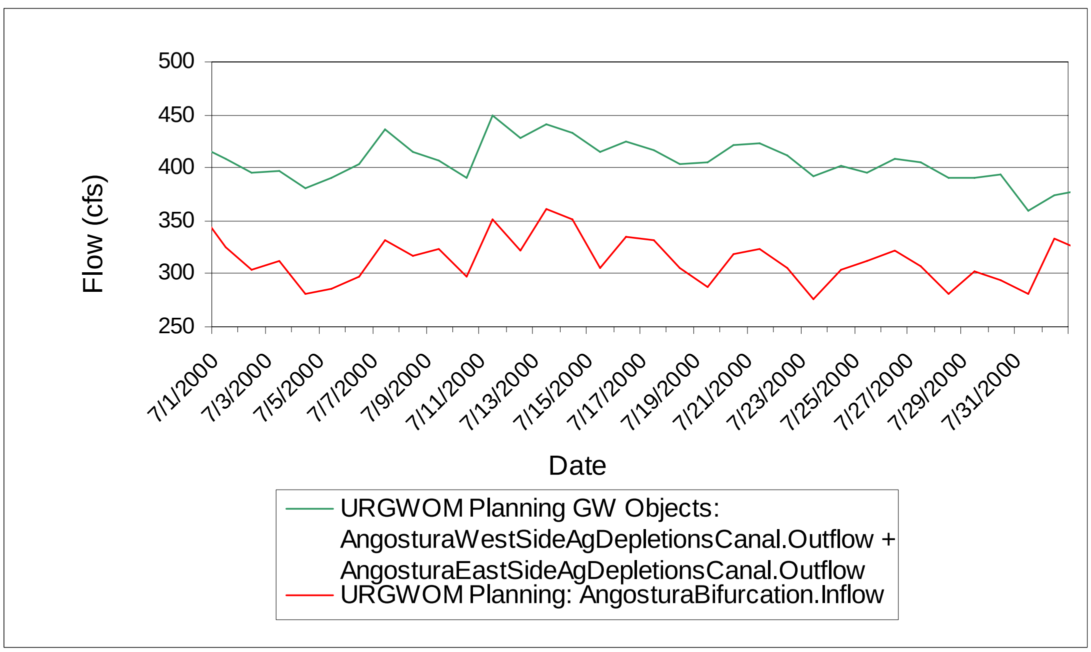


Figure 4.43) Lower Region: Flow Remaining in Canal After Irrigation and Deep Seepage/Percolation Losses Cochiti to Central Models – Water Balance Investigation.



At this point in the URGWOM Planning model, flow is returned to the main river channel. The amount of water returned to the river is determined using the Gage Fractional Flow method (on the CentralCombinedDrainsAndCanals object) and is based on the sum of what appears to be input gage data for gages which are not present in the URGWOM Planning GW Objects model (ArmijoAcequia, AlbRiversideDrainTingley, AtriscoDitchCentral, ArmijoAcequiaCentral). From a discussion with the USGS, NMISC, and USACE it was noted that the amount of water remaining in this canal is typically set using a RiverWare rule set, which is not present in this version of the URGWOM Planning model. Instead the URGWOM Planning model employs as described above a sum of gage inputs. In some cases, as shown in Figure 4.44, water is not returned to but extracted from the river in the URGWOM Planning model to meet the canal flow requirements (July 2, 2000 – July 5, 2000). In the URGWOM Plannning GW Objects model, all flow in the western canal is returned to the river. Canal returns to the river occur at two points: 1) UpperCorralesWasteWay and 2) WestSideReturn, which contains the sum of the reaming canal flow (just below UpperCorralesWasteWay) and the SanFelipeToCentralDrainWest inflows. Since drain inflows (SanFelipeToCentralDrainWest4) are not present in the URGWOM Planning model, the summed total of canal returns shown in Figure 4.44 do not include this drain return. While all flow from the western canal is returned to the river, some flow is retained in the eastern canal. The method used to calculate the amount of flow remaining in the eastern canal is capped at 180 cfs so if 180 cfs is available, then any remaining flow is sent to the river and if less than 180 cfs is available then a percentage of that flow is returned to the river. As shown in Figure 4.44 and Table 4.7, the mean daily canal returns are approximately 205 cfs less in the URGWOM Planning model than in the URGWOM Planning GW Objects model. Figure 4.45 shows the quantity of water remaining in the canals after the returns to the river with a mean daily difference of approximately 109 cfs.

In summary, in the lower portion of the modeled region significant differences were noted in the values calculated by the two models for diversions, canal inflows, canal losses to groundwater, and irrigation consumption. Thus, the differences in model configurations and use of methods in the models produce an inconsistent picture of the region's water balance. Further, it is likely that these inconsistencies affect the quantity of seepage calculated in Scenarios 1 and 2, and currently the magnitude of these affects on seepage is unknown. The water balance differences between the URGWOM Planning and the URGWOM Planning GW Objects models make it difficult to evaluate a direct comparison of the seepage rates as calculated by the individual models.

Figure 4.44) Lower Region: Flow Returned to River from Canal(s) Cochiti to Central Models – Water Balance Investigation

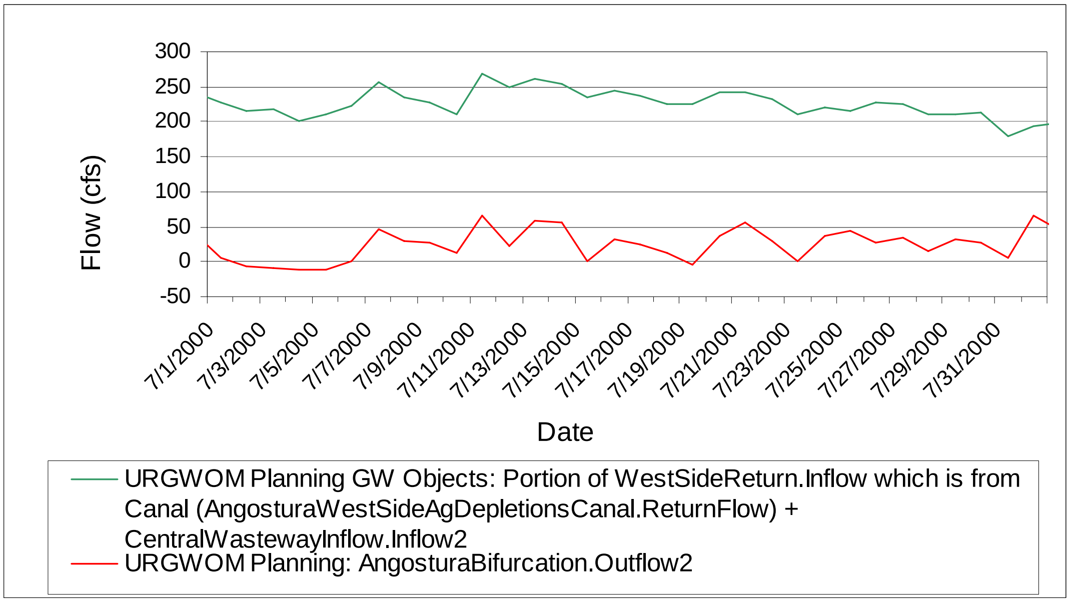
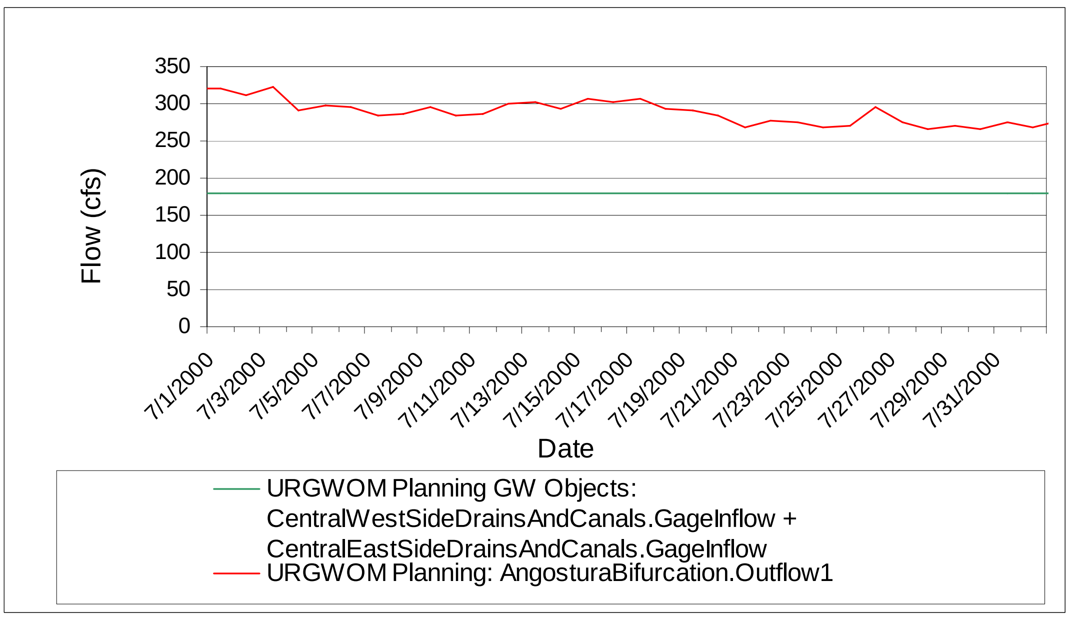


Figure 4.45) Lower Region: Flow In Canal After Returns to Main River Channel Cochiti to Central Models – Water Balance Investigation



4.6 Case Study 5: Sensitivity of Model to Low, Average, and High Flows at Predicted Future Conditions 2040-2041

This fifth case study compares runs using the RW-MF Linked model of the Cochiti to Central region during low, average, and high flow conditions at a future projected scenario beginning in 2040. As discussed in the model description section, the initial groundwater conditions used in this future scenario are based on those predicted by the regional groundwater model in a simulation optimization study which was aimed at minimizing groundwater drawdown over the region. Coordinated actions to minimize groundwater drawdown in the region are anticipated, thus the simulated results from this study provide insight into possible future groundwater conditions. As described in the model description section the inflow hydrographs for 1976-1977 (low flow years), 1999-2000 (average flow years), and 1984-85 (high flow years) were each run individually in the projected future scenario model.

Figure 4.46 shows flow at the gages for all three future scenarios. Figures 4.47 and 4.48 display river gain/loss for all three future scenarios by reach and by RiverWare object. It is important to note that since no predictions for the river diversions were available the diversion schedule from 1999-2000 was used in all future scenarios as can be seen in the Cochiti Canal at San Felipe gage in figure 4.46b. From the river gain/losses calculated for the individual Reaches**,** it is interesting to note that the greatest gain/loss variation between the low, average, and high river conditions, as well as, the largest spread in calculated seepage values, occurred in the SanFelipeToCentralSeepageArea4 the most southern Reach.

Figure 4.48 shows river gain/loss to the aquifer in the Upper and Lower regions of the model for all three future scenarios, as well as the gain/loss calculated by the RW-MF Linked 1999-2000 model. River gain/loss for average river flow at the projected future groundwater conditions produced results similar to the 1999-2000 results. Specifically, river gains estimated in the Upper portion of the model for average river flow conditions during 2040-2041 are slightly lower than in 1999-2000; and in the Lower portion of the model slightly greater river losses are predicted in 2040 than in 1999 and likewise for the beginning of 2041, however by the end of 2041 river losses are estimated to be less than river losses in 2000. Thus, average river flow conditions would likely have little effect on the projected future groundwater conditions. As shown in Figure 4.48 river gain/loss to the aquifer is more sensitive to flow changes in the river in the lower portion of the model than in the upper portion of the model. This result suggests that in the lower portion of the model at projected future groundwater conditions lowered river flows would produce drastically decreased seepage from the river to the aquifer, and could contribute to a lowered water table. Since the purpose of the 2006-2040 model projection was to minimize future groundwater drawdown, an extended future drought could substantially affect the position of the water table, especially if increased pumping were to occur during these periods. In contrast to the low river flow results, the future projection high river flows would induce greater river losses in the lower region and lesser river gains in the upper region, with several instances of river loss (Figure 4.48). These results suggest that an increase in the elevation of the water table under high river flows is possible. Based on the assumption that only relatively minor changes are observed in future groundwater conditions (no significant drawdown has occurred) from those recorded in 1999-2000, the results of the future projection suggest that although average and high river flow conditions would not have a negative impact on groundwater levels, however chronic low river flow conditions may have a significant negative impact.

Figure 4.46) Flow at Gages in RW-MF Linked Cochiti to Central Model Future Scenario (2040-2041) for Three Different Historical River Conditions.

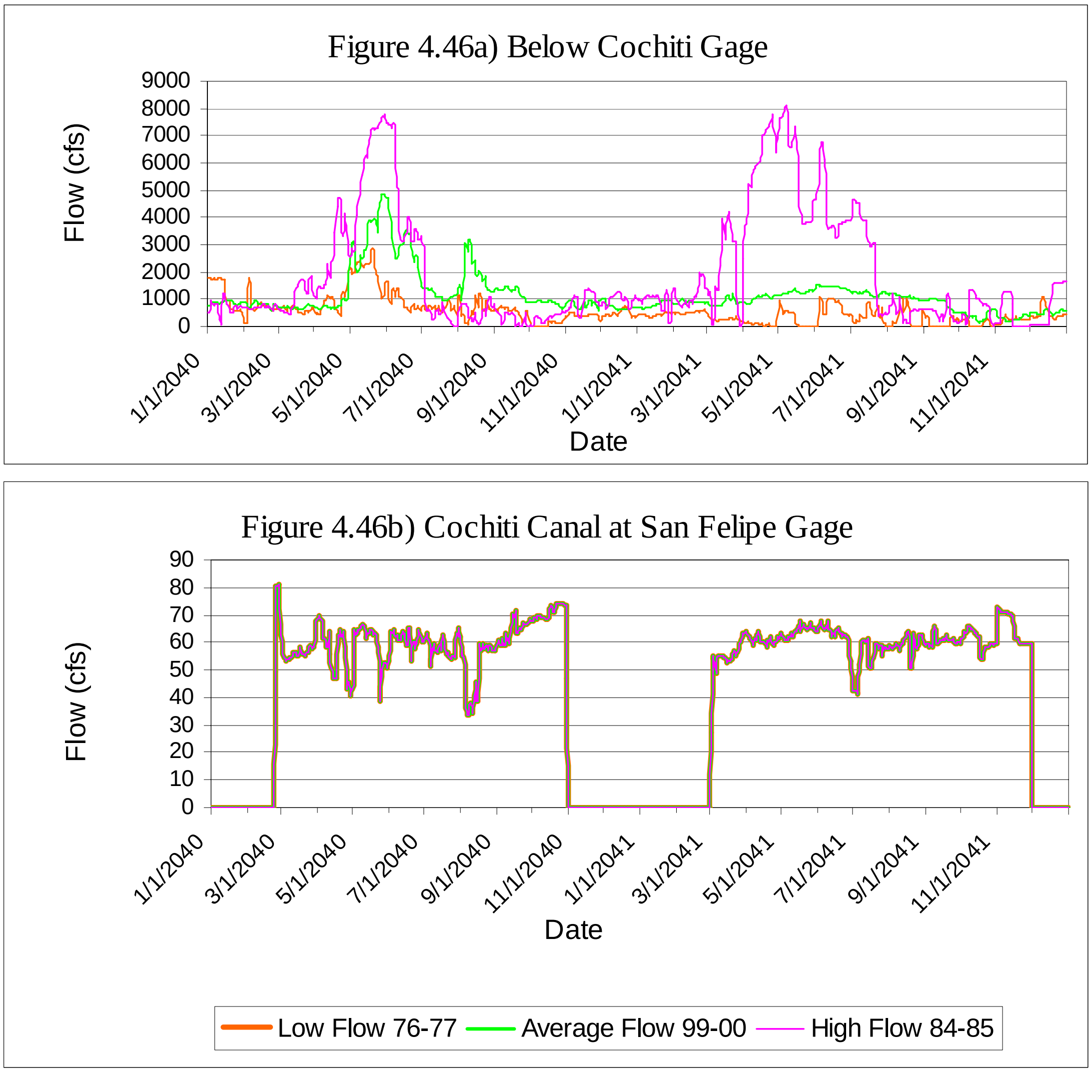
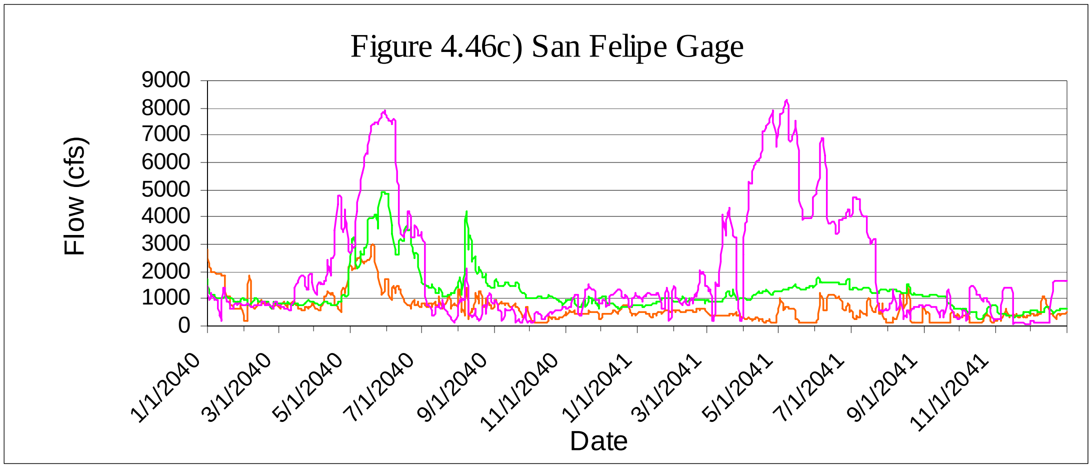


Figure 4.46 cont.) Flow at Gages in RW-MF Linked Cochiti to Central Model Future Scenario (2040-2041) for Three Different Historical River Conditions.



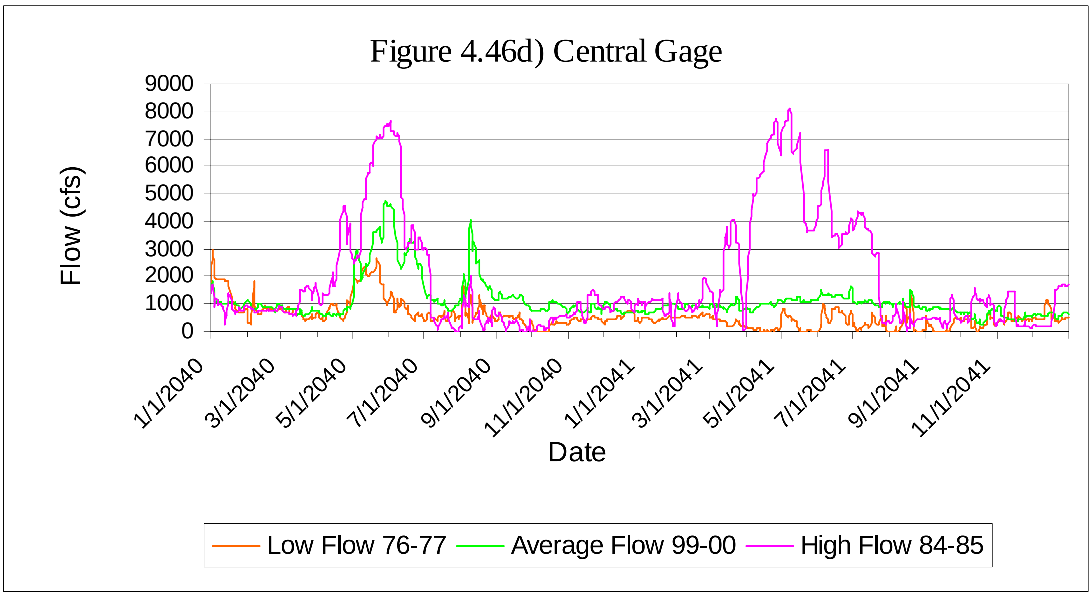


Figure 4.47) River Seepage/MODFLOW GainLoss for the RW-MF Linked Cochiti to Central Model Future Scenario (2040-2041) for Three Different Historical River Conditions. River Seepage is displayed by RiverWare object.

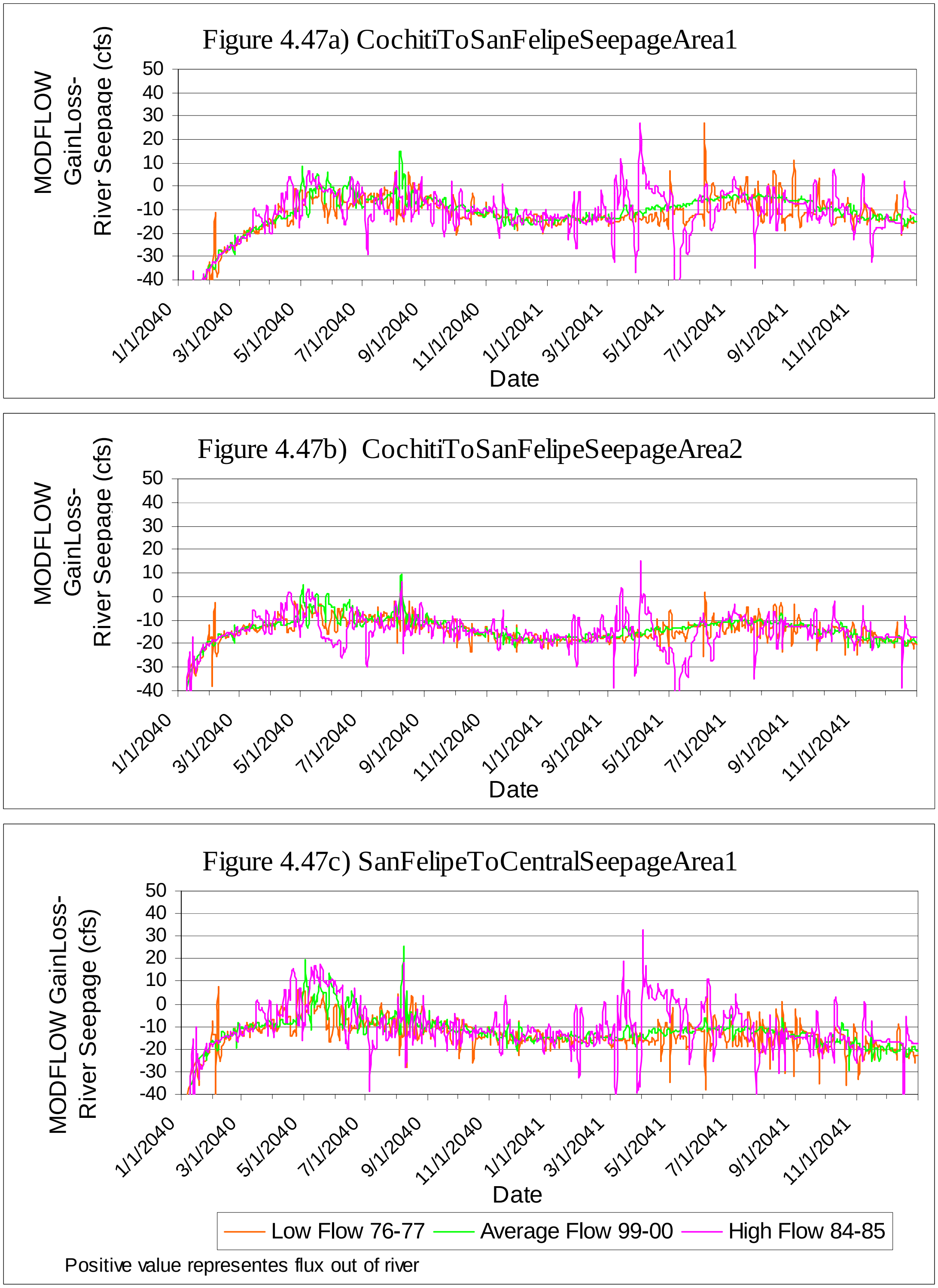


Figure 4.47 cont.) River Seepage/MODFLOW GainLoss for the RW-MF Linked Cochiti to Central Model Future Scenario (2040-2041) for Three Different Historical River Conditions. River Seepage is displayed by RiverWare object.

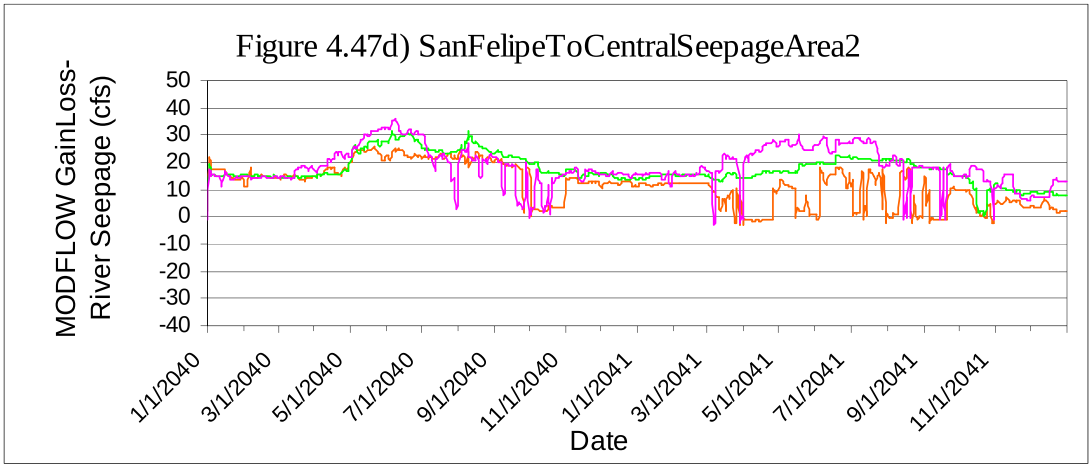


Figure 4.47d) SanFelipeToCentralSeepageArea2

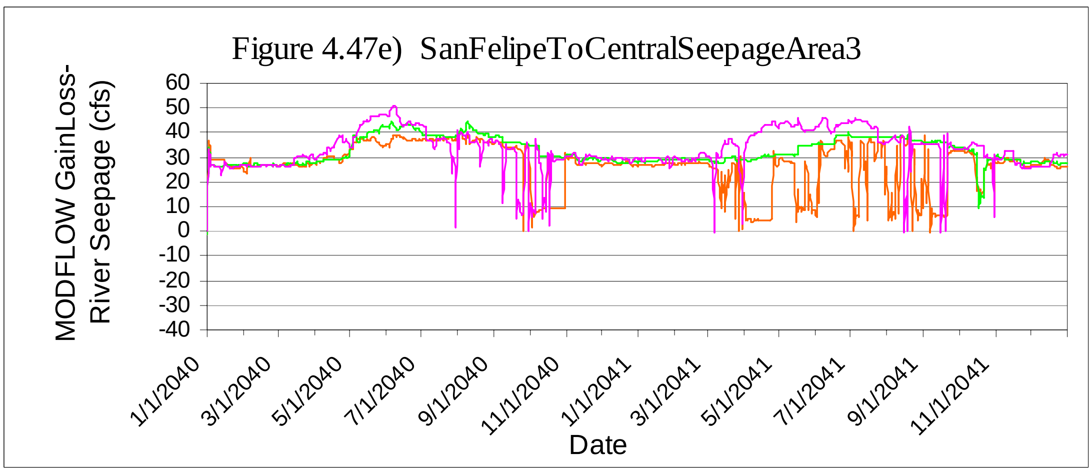


Figure 4.47e) SanFelipeToCentralSeepageArea3

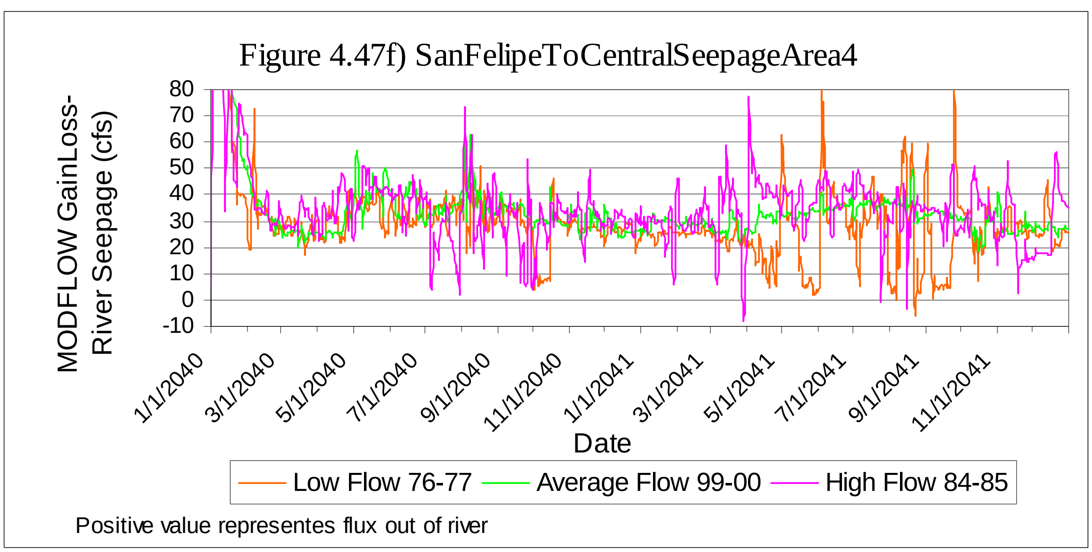
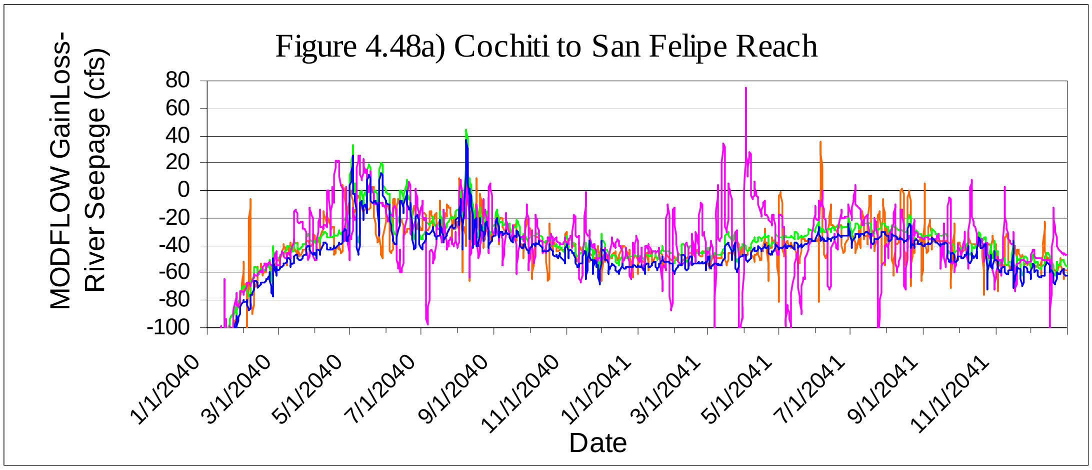
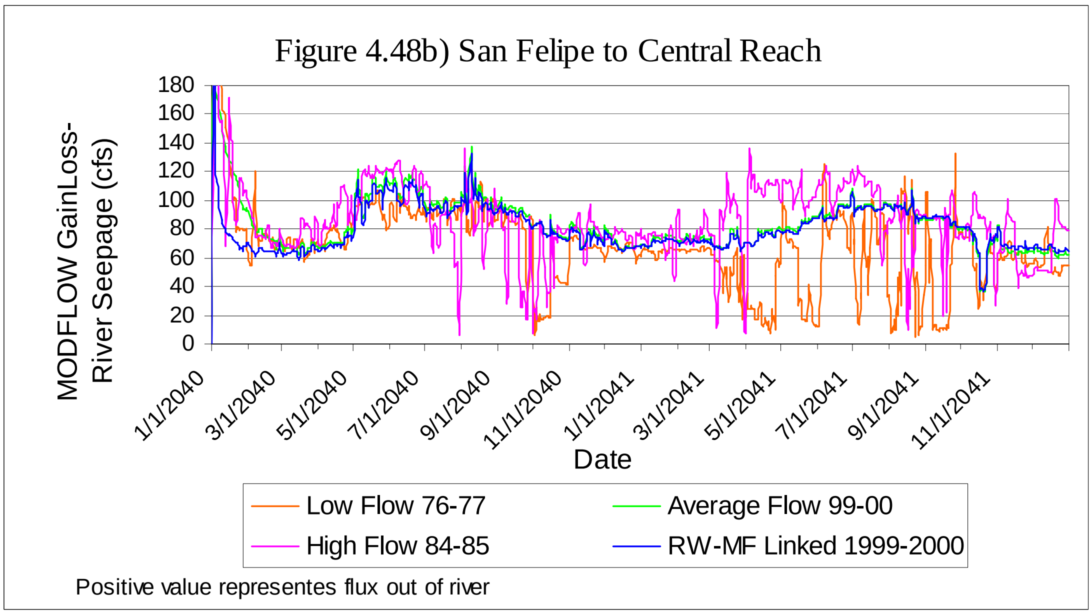


Figure 4.47f) SanFelipeToCentralSeepageArea4

Figure 4.48) River Seepage/MODFLOW GainLoss for the RW-MF Linked Cochiti to Central Model Future Scenario (2040-2041) for Three Different Historical River Conditions. Total River Seepage is displayed over each reach Cochiti and Upper Albuquerque.





4.7 RiverWare-MODFLOW Linked Model Performance

The time necessary to run the RiverWare-MODFLOW Linked models of the Middle Rio Grande Basin (2 year run at a daily time-step) was considerable. Variation in run times occurred depending on the computer and executable used, where the longest observed run time was, approximately 4.5 days and the shortest

19 hours. To date, no performance testing has been conducted on the linked model. Several reasons for the slow run times are suspected and two suggestions that may lead to improved performance are provided below.

1) Buddle exchanged data: currently, the network communication between RiverWare and the MODFLOW server consists of a single network access request for each exchanged data value (one value per each MODFLOW cell or segment), thus hundreds of thousands of values pass though the network connection at each time-step. Bundling data would decrease the amount of network traffic and could decrease run times.

2) Improve search algorithm within the MODFLOW server: currently, a linear search algorithm is used to find exchanged data (for replacement and extraction). A more efficient method for finding the location of the exchanged data within MODFLOW memory could decrease processing time.

CHAPTER 5 - SUMMARY AND CONCLUSIONS

5.1 Model Results Summary and Conclusions

A link between RiverWare and MODFLOW modeling programs was developed and tested. 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. Variables associated with MODFLOW's *RIV*, *STR*, *SFR*, and *GHB* packages can 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 the RiverWare objects the user is able to specify multiple MODFLOW cells as corresponding to a single RiverWare object. Accordingly, spatial interpolation and summation of some exchanged variables may be necessary. RiverWare's Computational Subbasin structure is used to handle this interpolation and summation and facilitates the mapping of MODFLOW cells to specific RiverWare objects. Variables that can be exchanged between the two modeling programs include: river stage; gain/loss between the river and aquifer; groundwater elevation; lateral boundary flux; and flow between small scale surface water bodies and the river channel (e.g. drains/canals).

The RiverWare MODFLOW Linked model structure was tested and verified to ensure all the linked model features function as intended. Small discrepancies were noted between the stage, head, and drain inflow/outflow values extracted from the outputs shown in the RiverWare and MODFLOW components of the linked model and were attributed to rounding errors. The RiverWare-MODFLOW Linked model was applied to the Middle Rio Grande Basin in New Mexico from just below Cochiti reservoir to the Central Avenue river gage in Albuquerque, NM and results from the model were validated. The validation was completed by comparing the RiverWare MODFLOW Linked model results against the results from the two MODFLOW models of the region executed independently of RiverWare (MFOnly models). While some simulated differences between the MFOnly models and the RiverWare-MODFLOW Linked model were found and could be attributed to input parameter and model configuration differences, the trends observed for river seepage, lateral flux and drain return flows were found to be consistent between the two models. Thus, the results produced by the RiverWare-MODFLOW Linked model were considered acceptable.

The model results for the RiverWare-MODFLOW Linked model of the Middle Rio Grande Basin in New Mexico from Cochiti to Central (RW-MF Linked model) were compared against historic data for two 2-year periods in which different river flow conditions prevailed (1999-2000 average flow conditions, and 1976-1977 low flow conditions). In both periods, the RW-MF Linked model was able to acceptably reproduce historic river flows. Results for the same two periods were also compared to two other models of the region, the URGWOM Planning and the URGWOM Planning GW Objects models. While all three models simulate acceptable flow in the river, overall during periods of extremely low flows, the RW-MF Linked model best matched historic data. The river gains/losses from/to the aquifer simulated by the RW-MF Linked model and the URGWOM Planning GW

Objects models are similar to one another and are very different from those produced by the URGWOM Planning model. The regression equation used in the URGWOM Planning model can only calculate seepage as a loss from the river, and this computed value is tied directly to historic flow data. From the differences noted in the results between this model and the other two models, it is suspected that several surface water features not present in the URGWOM Planning model are accounted for in the regression equation coefficients. Therefore, it can be stated that while the RW-MF Linked and URGWOM Planning GW Objects models do not necessarily produce significantly better river flow estimates than the URGWOM Planning model, they do produce more realistic values for estimated river seepage. As a side note, it was found that the seepage estimates produced by the URGWOM Planning GW Objects model were more sensitive to changes in river flow than the RW-MF Linked model and without further investigation it is not clear which of these models produces a more accurate estimate.

All three of the Cochiti to Central region models were subjected to two low inflow scenarios. The RiverWare-MODFLOW Linked model and URGWOM Planning GW Objects model produced similar river flows in both scenarios, and significantly different flows from the URGWOM Planning model. It was found that the URGWOM Planning model required greater river inflows to the region in order to produce the same volume of river outflow from the region. The large differences in outflow volumes calculated between the URGWOM Planning model and the other two models were unexpected, and differences in estimated river seepage could only account for about half of the noted discrepancy. Thus, an investigation was performed to track the remaining causes for this disparity. Initially, it was obvious that the representation of the irrigation canals in the two models differed. In the URGWOM Planning model the irrigation canals are modeled as a single entity which represents both the eastern and western canals, while in the URGWOM Planning GW Objects model the canals are modeled as two separate entities representing the eastern and western sides. When looking at the results from the historic comparison, it appears as if the model setups are simply two different ways of modeling the same region. However, from the low inflow simulation results it was found that the values computed for water losses from the canals and returns to the river from the canals were significantly different. Based on the above observations and the possibility that the URGWOM Planning model's seepage estimates are not realistic, it is recommended that caution should be exercised when using the URGWOM Planning model for operational planning during periods of low flow.

The effort necessary to construct the RW-MF Linked model was considerable, and it took approximately 1 to 5 days to run the 2-year long simulation. In contrast, the URGWOM Planning GW Objects model took only several minutes to run. Overall, both the URGWOM Planning GW Objects and RW-MF Linked models adequately reproduce historic gage flows. Since less effort was needed to create and run the URGWOM Planning GW Objects model, at this time, the most efficient model choice for operational modeling in the Cochiti to Central region near Albuquerque, NM is the URGWOM Planning GW Objects model.

5.2 Suggestions and Recommendations for the Middle Rio Grande Model Improvements

Along the canals, the same features are represented in the URGWOM Planning and URGWOM Planning GW Objects model with different object/method configurations. These configuration differences were found to produce inconsistent values of flow in several RiverWare objects during the low flow simulations. Thus it is suggested that an effort be made to update the canal computation methods/configuration/user inputs in the model that is deemed to be less accurate, so that all the models contain a consistent representation of these features. After completing this task, a new comparison of the models should undertaken, and will likely be able to provide more realistic insight into the differences in river seepage associated with these models.

More effort could be put into calibrating the RW-MF Linked model. Since the RW-MF Linked model was only run for two 2-year periods, and historic flow data is available for many additional years, it is suggested that an effort be made to further calibrate the RW-MF Linked model using additional periods from the historic record. Additionally, it is not clear which of the two models, RW-MF Linked model or URGWOM Planning GW Objects model produces better estimates for river gain/loss. Differences in the observed seepage estimates are due to the differences in conductance, area, initial storage, and initial elevation set on the RiverWare **GroundWater** objects and in the MODFLOW models. Calibration of these parameters may lead to river flow estimates that better match the historic record. In addition, adjustment of the selected routing method and its inputs set in the lower portion of the main channel of the river, may also improve modeled flow estimates. A larger difference between the modeled and historic flows was observed in the lower half of the modeled region, and there was some indication that the routing method used may contribute to these differences.

We have demonstrated that MODFLOW can be coupled with an operations model using an explicit solution exchange at each time-step, and that the coupled model results compare well with the finite difference solution produced by the MODFLOW-only model. Although, there are performance issues that need to be addressed, this study concludes that the linked RiverWare-MODFLOW model is a promising approach for managing river sections where dynamic groundwater-surface water interactions dominate surface water flows.

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