River Hydrograph Retransmission Functions of Irrigated Valley Surface Water–Groundwater Interactions

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Abstract: Storage and release functions of western U.S. traditional river valley irrigation systems may counteract early and rapid spring river runoff associated with climate variation. Along the Rio Grande in northern New Mexico, we instrumented a 20-km-long irrigated valley to measure water balance components from 2005 to 2007. Hydrologic processes of the system were incorporated into a system dynamics model to test scenarios of changed water use. Of river water diverted into an earthen irrigation canal system, some was consumed by crop evapotranspiration (7.4%), the rest returned to the river as surface return flow (59.3%) and shallow groundwater return flow that originated as seepage from canals (12.1%) and fields (21.2%). The modeled simulations showed that the coupled surface water irrigation system and shallow aquifer act together to store water underground and then release it to the river, effectively retransmitting river flow until later in the year. Water use conversion to nonirrigation purposes and reduced seepage from canals and fields will likely result in higher spring runoff and lower fall and winter river flow.

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Introduction

Irrigation seepage and its delayed return to adjacent water courses via groundwater discharge may serve as an important buffer to earlier and more intense spring runoff induced by climate variability. These effects on river flow could be highly beneficial, but have been poorly quantified in most locations. Increasing scrutiny of water use in the southwestern United States and other arid regions worldwide suggests that a broad perspective is needed to characterize hydrologic processes and inform effective water management. Comprehensive analysis is particularly needed to analyze linkages between irrigation, fluvial aquifers, and connected rivers in river valleys that are foci of human activity and ecosystem function.

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Demand for surface water and groundwater resources is outstripping supplies in many parts of the world (Jackson et al. 2001). In the United States, this problem is of particular concern in the Southwest. In the state of New Mexico, the population is currently increasing by over 1.5% per year, and most of this growth is projected to be concentrated in the urban areas along the Rio Grande corridor (Bureau of Business and Economic Research 2008), which traverses the state from north to south. Groundwater extraction continues to increase in some areas, causing declining water tables and decreased flow in Rio Grande tributary streams (Office of the State Engineer 2000; Zektser et al. 2005).

Countering groundwater extraction is recharge from irrigated areas. In southwestern U.S. river valleys a large percentage of stream/surface water is diverted for agricultural purposes; yet there are few studies to show to what degree irrigation system seepage and deep percolation recharge valley aquifers and the extent to which this recharge is delayed in time. A study in northern New Mexico showed that irrigation system seepage and percolation recharged a shallow alluvial aquifer (Fernald and Guldan 2006). Studies in California have shown that deep percolation can be a significant source of groundwater recharge beneath large irrigated areas (Schmidt and Sherman 1987). Paradoxically, efforts to increase water use efficiency may reduce groundwater recharge; in fact, lining irrigation canals can even cause groundwater levels to drop (Harvey and Sibray 2001). If lining canals reduces seepage rates and recharge to shallow groundwater, there may be less irrigation source return flow to rivers, particularly later in the later irrigation season when flows are traditionally low.

Rates of water seepage out of canals are highly variable and depend on many factors including soil texture and structure, bank and bed disturbances, sediment sealing, siltation, depth of water in the canal, length and shape of canal wetted perimeter, and other factors (Alam and Bhutta 2004). Reported canal losses include 16% of canal inflow (Fernald et al. 2007) and simulated 34–43% (Singh et al. 2006) and 15–20% (Schoups et al. 2005) of canal inflow. Aside from lining with impervious materials, seepage out of earthen channels can be reduced by compaction of the bed (Moghazi and Ismail 1997) or through natural aging or sealing processes (Smith 1982). However, significant seepage can take place in partially lined canals or lined canals with defects in the lining (Wachyan and Rushton 1987).

At the field scale, significant amounts of irrigation water have been shown to percolate below the crop rooting zone. Willis et al. (1997) calculated 31 and 23% deep percolations of total water infiltration in two different soil types. Under carefully planned irrigation scheduling, Asare et al. (2000) at a Kansas dry land site and Mankin and Koelliker (2000) at a New Mexico site simulated water losses below the rooting zone for alfalfa stands, and their results showed up to 50% deep seepage at both sites. Total percolation below the rooting zone in terms of total depth per year has been shown to range from 9.5 mm/year in south Australia (Leaney and Herczeg 1995) and 75 mm/year in Portugal (Stigter et al. 1998) to 202 mm/year in southeast Australia (Willis and Black 1996) and 290 mm/year in California (Young and Wallender 2002).

Seepage from irrigation canals has been shown to be an important source of recharge to shallow groundwater. Groundwater recharge from irrigation canals can cause groundwater mounds beneath the canals that dissipate when canal seepage stops (Maurer 2002). The rise and decay of groundwater mounds in response to deep percolation are affected by the shape of the recharging area (Hantush 1967). Modeling studies have illustrated the temporal transience of this groundwater mound in unconfined aquifers (Youngs 1977; Gill 1984; Yussuff et al. 1994; Ram et al. 1994; Upadhyaya and Chauhan 2001). In a system where seepage from unlined canals was 60 times greater than seepage from lined canals, seepage from the unlined canals dramatically increased groundwater flows and caused elevated water tables (Drost et al. 1997). Stable isotope and water chemistry studies confirmed the irrigation canal seepage origin of recharge that caused a rise in local groundwater levels (Harvey and Sibray 2001; Helmus et al. 2009).

Irrigated field percolation represents a large potential source of groundwater recharge (Leaney and Herczeg 1995; Willis et al. 1997). Diverse methods are available to investigate surface water and groundwater recharge interactions (de Vries and Simmers 2002; Scanlon et al. 2003; Sophocleous 2002). Some of these methods involve calculation of deep percolation rates based on crop-irrigation infiltration (Jaber et al. 2006; Sammis et al. 1982), measurements of water transmission losses (Fox et al. 2004; Hunt et al. 2001; Vázquez-Suñé et al. 2007), and the use of isotopes to reveal water hydrochemical interactions (Flint et al. 2002; Stonestrom et al. 2003). A straightforward approach to determine aquifer response to surface water inputs is the monitoring and modeling of changes in groundwater levels (Healy and Cook 2002; Sanford 2002; Sophocleous 1991). Though not widely available, estimates range from 50.8 mm/year in Idaho (Garabedian 1992) and 133 mm/year in southeast Australia (Chiew and McMahon 1991) to 350 mm/year (Willis et al. 1997) and 524 mm/year also in southeast Australia (Willis and Black 1996) and 640 mm/year in Nevada (Scanlon et al. 2005).

The few studies that have directly shown field deep percolation recharge to shallow groundwater illustrate the dependence of recharge rates on vadose zone soil structure. Ochoa et al. (2007) found that in a sandy loam soil, a significant percentage (25–60%) of water applied to a flood-irrigated alfalfa-grass mixture percolated below the root zone, and that a transient water table rise of up to 380 mm/year was associated with irrigation events. However, surface soil and subsoil characteristics, and irrigation method, can significantly influence the amount of deep percolation. Willis and Black (1996) concluded that the clay content in the B horizon appeared to be related to deep percolation rates. Also, Ochoa et al. (2009) found that soils with high clay content, or coarse soils with impervious clay layers, can reduce the velocity and quantity of water percolating through the vadose zone and reaching the water table.

Canal lining projects to improve conveyance efficiency and reduce seepage have resulted in lowering of groundwater levels. For example, lining irrigation canals and ditches is expected to reduce the availability of shallow groundwater supplying irrigation wells (Calleros 1991), irrigation and livestock wells (Harvey and Sibray 2001), domestic wells (Meijer et al. 2006), and water for nearby wetland ecosystems (Harvey and Sibray 2001). In other situations, however, seepage from canals and ditches can lead to excessively high water tables, potentially resulting in waterlogging and salinity problems (Gill 1984; Quinn et al. 1989).

Flowing streams provide water supply benefits to human activities and are associated with many ecosystem functions; yet there is incomplete understanding of the full connection from river-diverted irrigation to seepage and deep percolation to groundwater recharge and groundwater return flow to streams. A handful of studies have linked water management to groundwater-surface water interactions, addressing the irrigation to groundwater to river flow path. One study of the Methow River Valley in Washington showed that canal and field seepage recharge to shallow groundwater and subsequent return flow provided up to 20% of the total September river flow (Wissmar 2004), and irrigation seepage was important for connectivity between the floodplain and the Methow and Twisp rivers (Konrad et al. 2005). In Wyoming, irrigation seepage was shown to account for 65% of wetland inflows. One study in Montana linked the flow paths and showed that 50% of irrigation water became deep percolation and groundwater recharge, and that recharge in turn became groundwater return flow that augmented river flow (Kendy and Bredehoeft 2006).

In places where previously active meandering channels have been constrained by man-made structures, canal and field seepage may attenuate and redistribute peak flows, replacing hydrologic functions previously performed by floodplain relict channel features. Irrigated landscapes perpetuate wetland habitat and riparian habitats that are vital to terrestrial and aquatic ecosystem functions such as pollution buffer capacity, stream bank stabilization, allochthonous organic matter inputs, breeding habitat, and migration corridors. Interactions between surface water and groundwater also provide hyporheic exchange benefits to aquatic ecosystems. All of these functions are altered by and affected by irrigation applications and seepage. Full understanding of the benefits accrued requires full accounting and characterization of the hydrologic processes within the irrigated agroecosystem.

Tidwell et al. (2004) and Roach and Tidwell (2009) developed a system dynamics model of the Upper Rio Grande (Colorado border to Elephant Butte Reservoir) to aid in stakeholder-mediated regional water planning. The model is designed to be complementary and consistent with the higher fidelity water management models previously noted. Its primary purpose is to provide a vehicle for rapid scenario analysis, public outreach, and

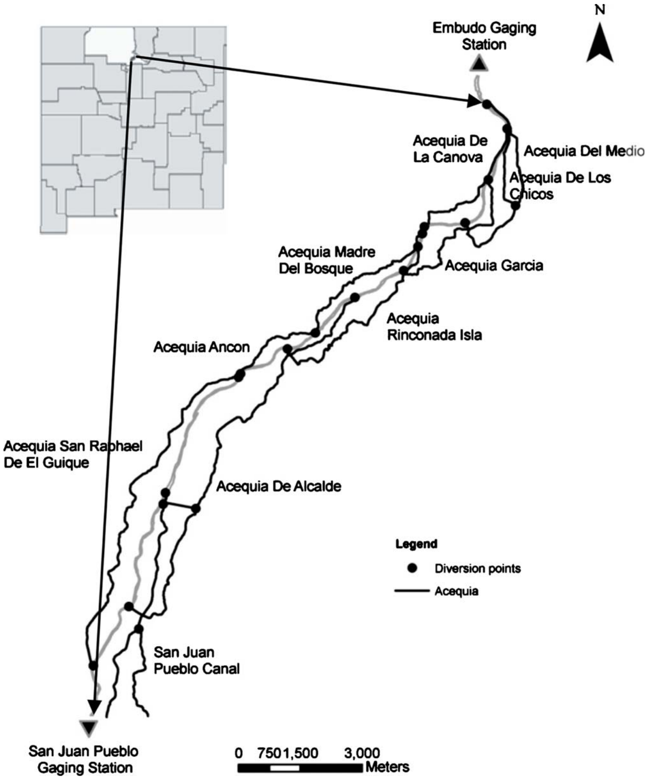

Fig. 1. Rio Grande surface hydrography from Embudo Station to San Juan Pueblo, showing acequia irrigation canals

education. While the model operates at a reduced temporal and spatial resolution it integrates surface water/reservoir routing, groundwater flow, and demand management functions within a single unified modeling framework. The coupled user-friendly interface provides an interactive environment for real-time "what if" analysis of competing water management alternatives.

The primary objective of this study was to determine the effect of irrigation system interactions with groundwater and their delayed influence on river flows. A detailed field measurement-based water balance was designed to advance scientific understanding of surface water-groundwater interactions in arid region valleys. Driven largely by the need to plan for the future and anticipate water management challenges, system dynamics modeling was employed to infer how surface water interactions with groundwater may change under different future land and water use scenarios. The combined measurement and modeling approach was used to test the hypotheses that (1) a substantial component of water diverted from the Rio Grande into traditional irrigation systems become canal and field seepage; (2) deep percolation of the seepage becomes shallow groundwater return flow to the Rio Grande; and (3) the shallow groundwater storage and release effectively minimize hydrograph variation by reducing peak flows and augmenting low flows, a highly valuable function under predicted future climate scenarios of earlier and more rapid spring runoff.

Study Area Description: Acequia System and Rio Grande Valley

This study focuses on a 20-km-long reach of the Rio Grande in north-central New Mexico (Fig. 1). Within this reach, traditional irrigation canals called *acequias* (Ah-say'-key-ahs) are used to divert water from the Rio Grande and distribute it to individual farms and fields primarily for irrigation and livestock watering. Croplands in this irrigated corridor are representative of many sites throughout the semiarid western United States. Alfalfa and pasture grass forages are grown on most of the irrigated acres in the valley and the region as a whole. Apples, chilies, sweet corn, and other high-value specialty crops are also important. Riparian vegetation along the riverbank is composed primarily of phreatophytic tree species such as willow, cottonwood, and Russian olive.

This reach of the Rio Grande is ideal for measurement and modeling studies. Upstream river flow data are available since 1899 from the Embudo Station, and historic downstream river flow data are available at the San Juan Pueblo Gauging Station (Fig. 1). Monthly mean daily river flow ranges from 10.8 m^3/s in September to 56.4 m^3/s in May with an annual average daily flow of 23.0 m^3/s (USGS 2009a,b). There are nine major acequias in the Black Mesa reach of the Rio Grande Valley (Fig. 1). Climate data at the Alcalde Science Center located at 1,733-m elevation show that the average maximum annual temperature is 20.1°C, and the average minimum annual temperature is 1.1°C; the average annual total precipitation is 251 mm (WRCC 2006).

Detailed process studies took place at New Mexico State University's Alcalde Sustainable Agriculture Science Center (Alcalde Science Center). The Alcalde Science Center occupies the corridor of land between the Alcalde Acequia, the main source of irrigation water, and the Rio Grande. The Alcalde Science Center provides 60 acres of irrigated land for research on various forage, fruit, vegetable, and alternative high-value crops using primarily surface flood or furrow irrigation, by far the most common practice in the valley and region. Soils include Fruitland sandy loam, Werlog clay loam, and Alcalde clay, typical of the range of soils found in the valley. This setting provides an ideal site to study surface water-groundwater interactions overlying a shallow fluvial aquifer and spanning the irrigated corridor from irrigation ditches to cropland, riparian areas, and a major river.

Several hydrologic modeling studies have been conducted in the Española Basin during the past two decades. These studies mostly focused on the Santa Fe and Los Alamos regions and the adjacent well fields. Besides hydrologic models, there are studies including geological/geophysical mapping, hydrological data collection and management, wastewater planning, and surface water modeling in different scales within the basin. Groundwater flow in the southern part of the Española Basin was modeled by Hearne (1985), McAda and Wasiolek (1988), Frenzel (1995), and Keating et al. (1999). Except for the Los Alamos National Laboratory model (Keating et al. 1999), these models partially cover the Black Mesa Reach of the Rio Grande. Although some detailed modeling has been done in the Española Basin, the existing groundwater model structures do not include surface water-groundwater interaction, lacking close examination of the relationship between shallow groundwater, canal seepage, and river flow.

Bexfield and McAda (2003) used a three-dimensional (3D) groundwater model prepared by McAda and Barrol (2002) as a basis for their model. The objective was to simulate the effects of groundwater management scenarios in the Santa Fe Group aquifer system in the Middle Rio Grande Basin adjacent to the Española Basin. The model was developed to integrate the components of the groundwater flow system including hydrologic interaction between the groundwater and surface water systems in the basin to better understand the geohydrology of the basin and provide a

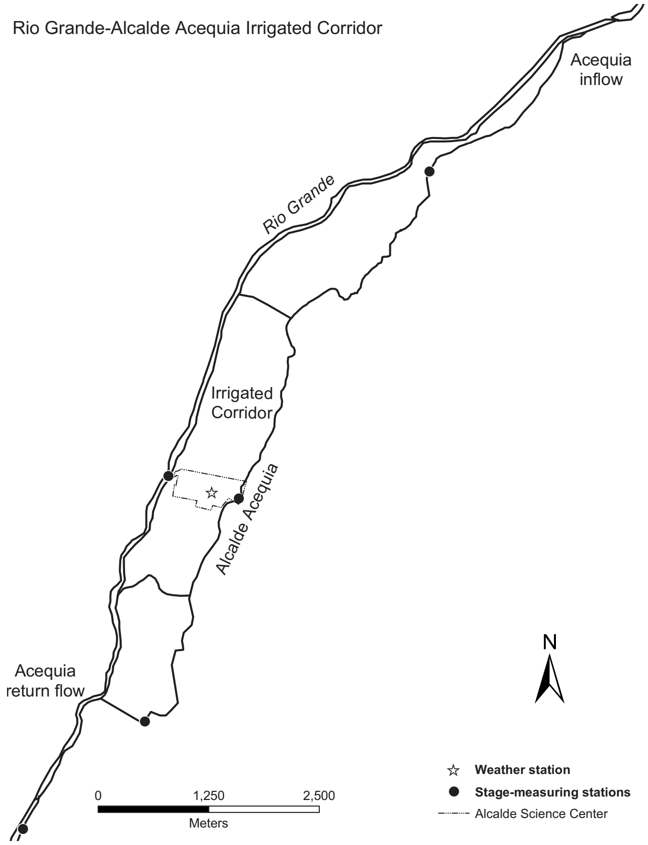

Fig. 2. Schematic of Alcalde Acequia with measurement locations

tool for water managers to plan and administer the use of basin water resources (Bexfield and McAda 2003).

Methods

Measurement Methods for Field-Based Water Balance of Water Diverted to an Irrigation Canal System

A field measurement approach was used to characterize the water balance of the area encompassed by the Alcalde Acequia irrigation system. Detailed measurements were used to account for all flows diverted from the river into the Alcalde Acequia irrigation canal. The Alcalde Acequia water balance was formulated as follows:

$$\begin{aligned}&\text{Canal diversion} - \text{canal seepage} - \text{canal turnouts}\\&\quad - \text{canal return to river} = \text{crop evapotranspiration}\\&\quad + \text{field tailwater} + \text{deep percolation}\end{aligned} \tag{1}$$

Canal discharge was calculated based on canal stage data collected at different locations along the Alcalde Acequia. Three stage-measuring stations were installed along the canal before the irrigation season of 2005. The first station was located at the northern portion of the canal before any water is diverted for irrigation, the second station was located at the NMSU Alcalde Science Center, and the third station was located at the southern part of the canal where no more water is diverted (Fig. 2). Each of the three stage-measuring stations was instrumented with a pressure transducer attached to a datalogger, which was programmed to record hourly water-level data. In addition, detailed measurements of stage and discharge were obtained after the irrigation season ended in November 2005 when there were no water diversions from the canal. Dataloggers were programmed to record stage data every minute while measurements of water velocity were made using a current velocity meter (Model 2100, Swoffer Instruments, Inc., Seattle, Wash.) following the six-tenths depth method used by the USGS (Buchanan and Somers 1976). Discharge was calculated using current velocity and stage data to develop canal stage-discharge rating curves at each stage-measuring station. Acequia diversion and return flows [Eq. (1)] are determined at the upper and lower gauging stations, respectively.

In 2005, an inflow-outflow test for calculating canal seepage was conducted after obtaining the canal stage-discharge rating curves. Water flowed in the canal during six consecutive days with no diversions and with no flow control other than the river inflow variations. After correction for evaporation, average time of arrival and stage-discharge measurements at the north and south stations were used to determine canal seepage over the 7.9-km canal transect. An average time of arrival of 6.4 h from the northern station (inflow) to the southern station (outflow) was calculated. Ditch seepage was calculated based on the difference in canal flow observed at the two stations.

In addition to the primary control structure at the acequia inflow, there were two turnouts used to control flow along the Alcalde Acequia. The first was located 5,000 m south of the Alcalde Acequia inflow, and the second was located 2,450 m north of the canal return flow (Fig. 2). The amount of water being diverted into these turnouts depended on the canal water inflow. Inflow exceeded the capacity of the canal at times, especially during flash flood events and made necessary water diversions into the turnouts to prevent flooding. A swoffer-current flow meter was used to measure canal flow at these turnouts periodically throughout the season.

We calculated the amount of water being diverted for irrigation by subtracting canal seepage, turnouts' return flow, and canal return flow from canal diversion. It was assumed that this total amount of water was used for crop-irrigation purposes. The irrigation component of the water balance was subdivided into crop evapotranspiration (ET), tailwater, and deep percolation.

In 2004, a weather station was installed at the Alcalde Science Center for measuring different climate variables that were used to calculate the reference ET. Precipitation data were obtained from a NOAA Weather Station present at the Science Center. These climatic and precipitation data were used with the root zone water quality model (Ahuja et al. 2000) for simulating the water balance for an alfalfa-grass field at the Science Center. Weather data were used to calculate crop ET using the FAO Penman-Monteith equation and dual crop coefficient under standard equations for other crops (Allen et al. 1998). A survey was conducted to determine the amount of land used for different crops in the irrigated valley. Total ET was calculated based on the percentages of cropland in the valley.

Because of reliable river source water availability in the valley and because of widespread traditional acequia water use practices, excess water applications to the fields are common. A frequent result is significant runoff, termed field tailwater that returns directly to the Rio Grande. In 2007, we conducted a study at the Alcalde Science Center to quantify field tailwater. We established two oat fields that were managed using locally adopted management and irrigation practices. We measured field tailwater using Samani-Magallanez flumes (Samani and Magallanez 2000) equipped with pressure transducers and dataloggers.

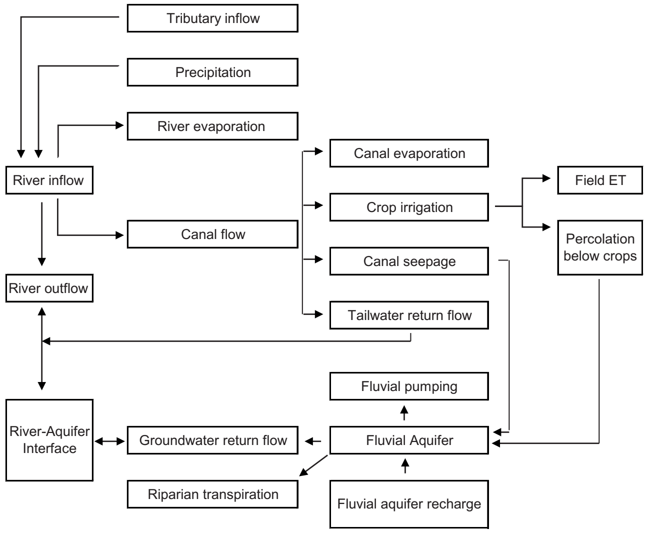

Fig. 3. Conceptual model of Rio Grande Valley water balance as incorporated into system dynamics model

Border and furrow surface irrigation are by far the most common types of irrigation practices in the area. At the Alcalde Science Center, we conducted several studies to determine deep percolation rates in different crop and soil types that are representative of the Alcalde valley (Ochoa et al. 2007, 2009; unpublished data). These field-based calculations of deep percolation obtained at the Alcalde Science Center were extrapolated to the entire valley, assuming similar soil, crop, and irrigation management practices.

Two stage measurement stations were installed in the Rio Grande. One station was installed near the Alcalde Science Center in April of 2005. The second station was installed under the bridge on State Rd. 74, which is the southern boundary of our study area, in March of 2008. Both stations are instrumented with a stand-alone water-level logger. Water-level data recorded on an hourly basis were converted to monthly averaged river stage.

Methods for Valley-Scale Hydrologic Characterization and System Dynamics Modeling

A dynamic water-budget model was developed that included all major hydrologic fluxes in the Rio Grande Valley between Embudo Station and San Juan Pueblo Station (Fig. 1). The model is formulated according to system dynamics stock and flow architecture. Basic water-budget elements and their network structure are given in Fig. 3. Estimates of each hydrologic component were derived from project measurements and analyses, public data sets, and literature values. The model operates on a monthly time step, using the period from 1973 to 1984 for calibration. Within the Embudo to San Juan Pueblo reach all water-budget values were calculated as spatially averaged elements. To the extent to which they are supported by available data, water-budget values were modeled as varying both seasonally and from year to year.

The upstream head of the study valley location was shortly downstream of Embudo Station, the oldest continuously operating (1889–present) USGS Gauging Station (USGS 2009a). USGS data were used for flow from Embudo Station and the downstream San Juan Pueblo Gauging Station, which had a shorter period of record from 1973 to 1984. Climate data were taken from the Española Weather Station 8 km south of the study area.

Fig. 4. Borehole well log locations used to determine gravel aquifer extent

Interaction of river flow and the shallow groundwater in the modeled portion of the river occur along the highly conductive river deposits. The modeled unconfined aquifer unit is composed of medium-sized gravel deposits of the ancestral Rio Grande. Analysis of correlations between 144 domestic well borehole logs from the New Mexico Office of the State Engineer (OSE) wells' database yielded the lateral and vertical extents of the river gravel (RG) fluvial aquifer (Fig. 4).

The RG has not been considered as a separate unit in the previous modeling efforts in the region. The hydraulic conductivity values reported in the literature are for the upper portion of the Tesuque Formation, Santa Fe Group. The group consists of interbedded silty sandstone, mudstone, and occasional thin conglomerate and ash beds. Consolidation and cementation vary greatly laterally and vertically. Bedding is commonly irregular, lithologic units are discontinuous, and sorting is poor, typical of alluvial fan deposits. Recent alluvium composed of silt, fine sand, and gravel occupies all of the stream and arroyo channels in the area, the thickest and most extensive being that in the valleys of the Rio Grande (Borton 1974).

One of the components of the discharge from the groundwater basin is groundwater pumping. The sources of groundwater extraction considered in the model are withdrawals by mutual domestic wells and withdrawals by domestic users. Only a small portion of the withdrawals from the domestic wells is used for lawn irrigation; the rest is consumed for indoor use. Although there is an increase in the number of domestic wells in the area since the 1980s, the use of groundwater for irrigation is not significant. The data obtained from the Mutual Domestic Water Consumers Associations in Alcalde and Velarde gave the withdrawals from four mutual domestic wells in operation and the total extraction from these wells, averaged for summer and winter. The average extraction was calculated as the weighted average of

Table 1. Field Water Use by the Main Agricultural Classes Determined by Survey of Irrigators

Land use/crop type	Growing season	Irrigation season	Irrigation frequency	Applied irrigation/month
Orchards	Apr.–Oct.	Apr.–Nov.	3 times a month	16.5 cm (6.5 in.)
Row crops+small veg.	Apr.–Oct.	Apr.–Nov.	3–4 times a month	25 cm (10 in.)
Alfalfa	Apr.–Nov.	Apr.–Nov.	2–3 times a month	20 cm (8 in.)
Grass	Apr.–Nov.	Apr.–Nov.	2–3 times a month	20 cm (8 in.)
Alfalfa+grass	Apr.–Nov.	Apr.–Nov.	2–3 times a month	20 cm (8 in.)

summer and winter months, assuming that there is a 25% increase in water use in summer based on the available data. Currently, there are 430 active members in the area that represent a household or a facility such as school, church, etc. Withdrawals for domestic purposes were calculated based on the mutual domestic well records and the well information obtained from the New Mexico OSE's database. Of the 908 wells in the database, 811 were coded as domestic wells.

Groundwater recharge occurs through infiltration from ungauged arroyos and from mountain-front recharge along the eastern boundary of the modeled area. The recharge along the western boundary is negligible compared to the eastern boundary. Numerous lines of evidence indicate that the majority of recharge to the basin aquifers occurs in the mountains along the basin margin where precipitation rates are relatively high (Keating et al. 2005). The upland networks of major stream valleys in the Sangre de Cristo Mountains are the primary source areas for recharge of basin-fill aquifers in the region. The water yield from the Sangre de Cristo Mountains was calculated from a regression model of 16 basins in or adjacent to the Rio Grande Basin in New Mexico previously developed by Hearne and Dewey (1988). The model was expressed as a multiple linear regression of mean annual water yield against mean winter precipitation

$$Q = 7.62 \times 10^{-5} \times A^{0.977} \times P^{3.596} \tag{2}$$

where Q=annual water yield (ft^3/s); A=area of the basin (mi^2); and P=mean winter precipitation (in.). The regional recharge into the Velarde subbasin was available in the Jemez y Sangre Regional Water Plan Report for New Mexico (D.B. Stephens & Associates and Lewis 2003). The area of the Velarde subbasin is slightly larger than the model domain area; so the tributary inflow was adjusted based on the ratio of Velarde subbasin area to our modeling domain area.

The canal diversions and the return flows were calculated based on field measurements of canal discharge. The velocity measurements were taken during the month of August in 2007 in order to capture the high-flow season. The measurement locations were selected as close as possible to the river for more accurate calculations of the diversions and return flows from or to the river. A digital velocity meter was used to measure the velocity of the water in the canals. Each irrigation canal was divided into at least 10 sections in order to create a velocity profile. The depth of the flow was measured at each point where the velocity was measured. The inflow and outflow for each irrigation canal were calculated by using the equation below (Carter and Davidian 1968)

$$Q = \sum V_i A_i = V_i \times (d_i h_i) \tag{3}$$

where Q=discharge (ft^3/s); V=velocity (ft/s); A=cross-section area (ft^2); d=depth; h=width; and i=interval number. The seasonal variations in Alcalde Acequia flows were used in concert with valley-scale measurements to model valley-scale water balances.

In order to characterize the agricultural practices and water consumption in the modeled portion of the valley, a crop and water use survey was conducted. The results of the survey help identify the crop types, crop acreage, and irrigation water consumption as well as the general land-use classification in the modeled area.

The land-use classification map of the area was prepared by using standard geographic information system (GIS) techniques. The most recent colored areal images of the region were used to differentiate between the crop types and other land-use classes such as residential, water bodies, evergreen forests, riparian vegetation, rangelands, orchards, etc. The key locations were ground checked in order to make sure that the areal interpretation was done correctly and the images reflect the current land use in the area. ArcGIS 9.2 (Environmental Systems Research Institute, Redlands, Calif.) tools were used to calculate the irrigated acreage and the areal extent of the other land-use classes.

The riparian vegetation delineated from the images was classified under two groups: riparian vegetation along the river and riparian vegetation along the acequias. The dominant riparian vegetation type in the area is cottonwood followed by Russian olive and New Mexico olive. The percent distribution of the riparian vegetation was determined from the fieldwork conducted along the midsection of the modeled area and extended to the whole valley.

Field water application practices for the orchards, alfalfa, grass, and row crops were estimated by the crop survey conducted during the research. The irrigation pattern of the large producers was assumed to represent the whole valley. Table 1 shows the irrigation frequency and monthly applied irrigation amount for the main agricultural classes in the region. Percolation below the plant rooting zone was determined at the Alcalde Science Center (see above) and applied, by crop type, to the entire valley.

Evaporation from free water surfaces and ET from crop and riparian vegetation areas were estimated for the Rio Grande Valley. Crop and riparian ET was calculated with a modified Penman-Monteith approach parameterized with local values from the ET toolbox (Brower 2008) and monthly averaged climate data from the local Española Weather Station. Crop ET values were further constrained according to normal irrigation practices using a stress factor based on the irrigation survey results noted above.

Rio Grande main stem inflows are based on historical data from the Embudo gauge. River stage is calculated using average channel morphology characteristics, while accompanying variation in shallow groundwater levels is based on seasonal transients in seepage from conveyance channels and irrigation deep percolation (calibrated on limited groundwater level data). Differences in river stage versus groundwater head drive river-aquifer interaction and were modeled according to a general Dupuit formulation (Fetter 2001).

Table 2. Alcalde Acequia 3-Year (2005–2007) Averaged Water Balance

Component		Amount from canal diversion (%)	Range (%)
Surface water return flow	Turnouts	9.5	0–14
	Crop field tailwater	8.9	0–19
	Canal outflow	40.9	28–67
Groundwater return flow	Ditch seepage	12.1	5–17
	Deep percolation	21.2	9–32
Evapotranspiration		7.4	1–15
	Total	100.0	

Results

Irrigation Canal Water Balance Results

For a 3-year period of record (2005–2007) it was calculated that the average Alcalde Acequia inflow for the irrigation season (April–November) was $3{,}275{,}823$ m^3 month^{-1} and that canal outflow was $1{,}314{,}988$ m^3 month^{-1}. During the 3-year period, canal seepage averaged 12.1% of the total inflow, ranging from 5 to 17% depending on canal flow rate (Table 2).

On average 9.5% of the total water diverted into the canal returns back to the river as surface return flow through the two turnouts. Turnouts' return flow ranged from 0 to 14% depending on canal inflow and amount of water being diverted for irrigation (Table 2). It was calculated that, on average, 37.5% of total canal inflow was used for irrigation purposes, ranging from 20.9 to 51.4%. Crop ET represented, on average, 7.4% of total water diversion (Table 2).

Our results showed that on average for the two crop fields, irrigation tailwater was 24% of the total water applied (Table 2), ranging from 0 to 40% depending on amount of water applied, slope, soil type, and antecedent soil moisture. Results from this study are similar to those observed in other crop fields in the area and to observations expressed by local producers. These results were used at the entire Alcalde valley scale, assuming similar irrigation and management conditions. Deep percolation averaged 56% and ranged from 37 to 63% of total water used for irrigation.

Rio Grande Valley Water Balance and System Dynamics Model Results

The distribution of the wells used for the correlation to delineate RG is shown in Fig. 4. The thickness of the RG unit varies between 24 m at its thickest point and 0.5 m at the thinnest section with an average thickness of 10.4 m. The thickness of the gravel increases toward south. The width of the unit is 2,755 m at its widest cross section and 176 m at the narrowest part on the northern end of the modeled portion of the river. Total fluvial aquifer areal extent is $3{,}728{,}301$ m^2.

Surface hydrographic features were delineated from ground-truthed GIS coverages. Total river reach length on the Rio Grande from Embudo Station to San Juan Bridge is 22,916 m (Table 3, Fig. 5). The upper part of this reach is a bedrock canyon without an underlying gravel aquifer. Reach length over which there was river-aquifer interaction was 20,010 m from the canyon mouth to the San Juan Bridge. Average channel width is 39 m. Average distance from the irrigation canals to the river was 281 m.

The reported horizontal hydraulic conductivity values range between 0.01 and 1 m/day (McAda and Wasiolek 1988; Frenzel 1995; Koning et al. 2007). Hawley and Kernodle (2000) reported a horizontal hydraulic conductivity range of 10–30 m/day for the RG portion of the Santa Fe Group lithofacies' assemblages. For the modeling purposes, hydraulic conductivity was set to 25 m/day.

Table 3. Inflow and Outflow Measurements in Rio Grande Valley Acequias

Measurement point	Flow (m^3/s)
San Juan Pueblo ditch outflow	0.34
Alcalde Acequia diversion	1.37
Alcalde Acequia return	0.54
Canova Acequia diversion	0.56
Canova Acequia return	0.41
Bosque Acequia diversion	0.34
Bosque Acequia return	0.1
Ancon Acequia diversion	0.2
Ancon Acequia return	0.1
El Guique Acequia diversion	0.26
El Guique Acequia return	0.08
El Medio and Chicos combination diversion	0.31
El Medio and Chicos combination return	0.13
El Medio Acequia diversion	0.26
Chicos Acequia return	0.08
Garcia Acequia diversion	0.2
Garcia Acequia return	0.05
Rinconada Isla Acequia diversion	0.08
Rinconada Isla Acequia return	0.02

For the four mutual domestic wells in operation, the total extraction from these wells, average of summer and winter, is about 2.5 million gallons per month ($9{,}500$ m^3/month) serving about 1290 people. The remainder of people (about 4000) in the valley get their water from domestic wells, with total extraction for indoor use from these wells calculated to be $30{,}000$ m^3/month. Based on the total extraction for domestic purposes, per capita water use was estimated to be 7.3 m^3/month. This number was reported to be 7.8 m^3/month for an individual living in a single-family home in the United States (Vickers 2001).

According to Eq. (2), the total regional aquifer discharge into the alluvial gravel aquifer was calculated as $451{,}500$ m^3/month. Based on McAda and Wasiolek (1988), a regional recharge rate of $451{,}500$ m^3/month was used for the modeling effort. Ephemeral wash tributary inflow was reported to be 175 acre ft/month (Jemez y Sangre Regional Water Plan 2003).

Delineated major land-use class areas are shown in Fig. 5, and calculated areas for each land-use class are given in Table 4. Mixed alfalfa and grass have the largest areal extent (5.39×10^6 m^2) followed in total area by riparian vegetation (3.73×10^6 m^2), orchards (2.21×10^6 m^2), and row crops (1.00×10^6 m^2), with small amounts of alfalfa and grass monocultures.

The system dynamics model was successfully constructed and closely reproduced measured river flow (Fig. 6). The system dynamics model allows scenario testing of aquifer-river interactions with and without irrigation diversions. Aquifer discharge to the river is reduced without diversions (Fig. 7). Compared to the scenario without diversions, there is less summer flow and more winter flow with irrigation diversions (Fig. 8).

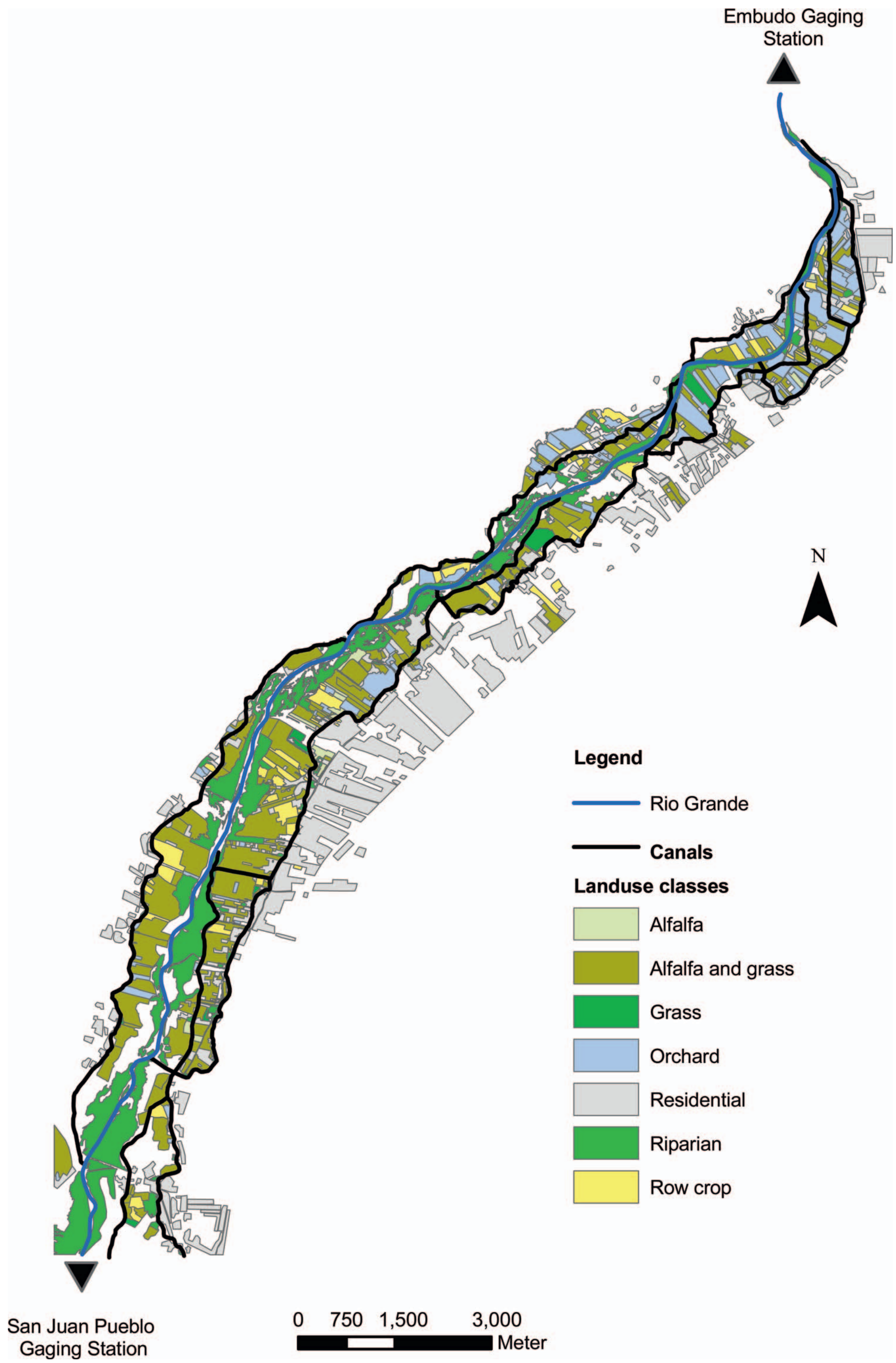

Fig. 5. (Color) Land-use classes in the modeled region

Table 4. Land-Use Classes and Calculated Areas

Land-use class	Area (m^2)
Alfalfa	205,264
Alfalfa and grass	5,392,577
Grass	211,559
Orchards	2,211,166
Row crops	1,000,161
Total crops	9,020,727
Riparian vegetation	3,728,301

Sensitivity Analysis

A series of sensitivity analyses was performed in order to identify parameters that affect the model most in terms of change in river-aquifer interactions. For this purpose, saturated hydraulic conductivity, specific yield, ET, RG area, riparian vegetation area, and recharge into the modeled area were increased in the amounts defined by a range of multipliers, and the model's response on a yearly averaged basis was plotted against the change in each parameter. The sensitivity analysis showed that the river-aquifer in-

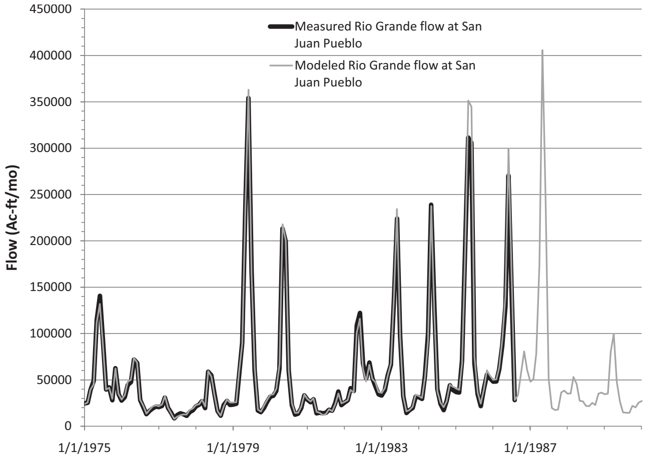

Fig. 6. Measured (San Juan gauge) versus modeled (system dynamics) Rio Grande flow at the study valley outlet

teraction is highly responsive to changes in saturated hydraulic conductivity of the RG unit (Fig. 9). The amount of water exchanged between river and aquifer increases with an increasing hydraulic conductivity. Increase in aquifer recharge along the model boundaries yields similar results with a lower magnitude response.

For a number of parameters, the model seasonal response varied, but the mean annual response was little changed. Assigning larger specific yield values to the RG unit reduces variation in the river-aquifer interaction (Fig. 9). The reduction in the exchange displays an exponential relationship with any increase in specific yield values. ET stress factor and riparian area increases create an exponential decrease in the river-aquifer interactions due to increasing outflows from the modeled system. Increase in ET stress factor creates twice the decrease caused by the increase in riparian acreage. Similarly, increase in the total RG area creates an exponential decrease in the river-aquifer interaction which could be attributed to water level decreases in the modeled area. In other words, with components such as recharge held the same, but with a larger RG area, there would be a decrease in water levels in a confined area; the river stage and the groundwater could reach equilibrium, thus decreasing the amount of interaction between river and aquifer compared to the initial conditions.

Discussion

Inclusion of all major hydrologic fluxes in our study of valley floodplain water movement allowed us to determine the relative magnitude of individual components. For the Alcalde Acequia, one-third of all water diverted for irrigation became field and ditch seepage that recharged groundwater, crop ET constituted only 7% of diverted water, and the remainder returned to the river as ditch and field surface return flows. Studies focusing on individual fluxes may fail to show their relative importance in the broader picture of water use. Surface return flows are quite large in this system. Actual consumption of water by ET, while in the normal range documented on a daily basis for this setting, is a small component of overall water use, and total water consumption is low.

System dynamics model tests of a scenario without seepage show the importance of ditch seepage and below-field deep percolation as sources of groundwater recharge, return flow to the river, and river hydrograph retransmission. Groundwater recharge is dramatically reduced without seepage, and similarly reduced is the river recharge from shallow groundwater return flow. The connection between irrigation and groundwater historically led to common understanding that domestic well water levels rise when irrigation begins in the spring each year. Beyond this localized effect of increased groundwater levels, seepage has important valley-scale and basin-scale effects on river flow. The seepage is stored underground in the shallow aquifer and returns to the river over a period of weeks to months, depending on the distance and gradient from the irrigation canal to the river. Hydrograph retransmission is the net effect of river water diversion into the irrigation system, seepage, storage underground, and delayed return to the river. The spring runoff peak is reduced, and fall and winter low

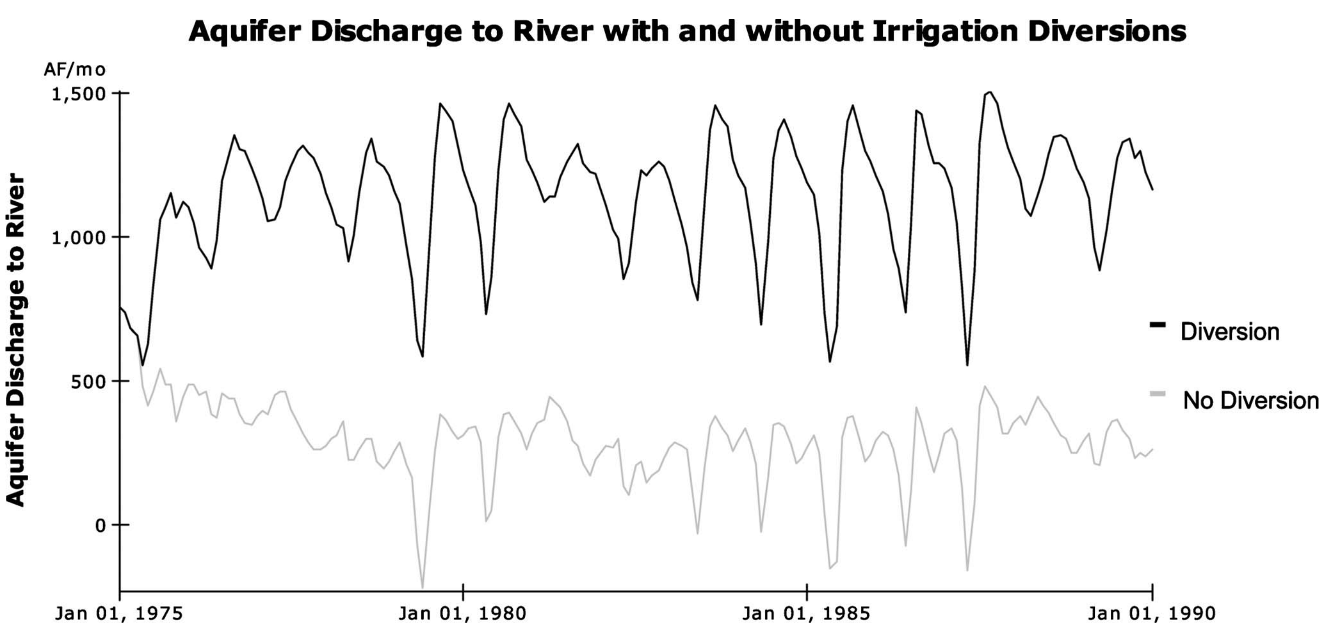

Fig. 7. Effects of diversion on groundwater return flow to river

Difference in River Flows with Diversions and without

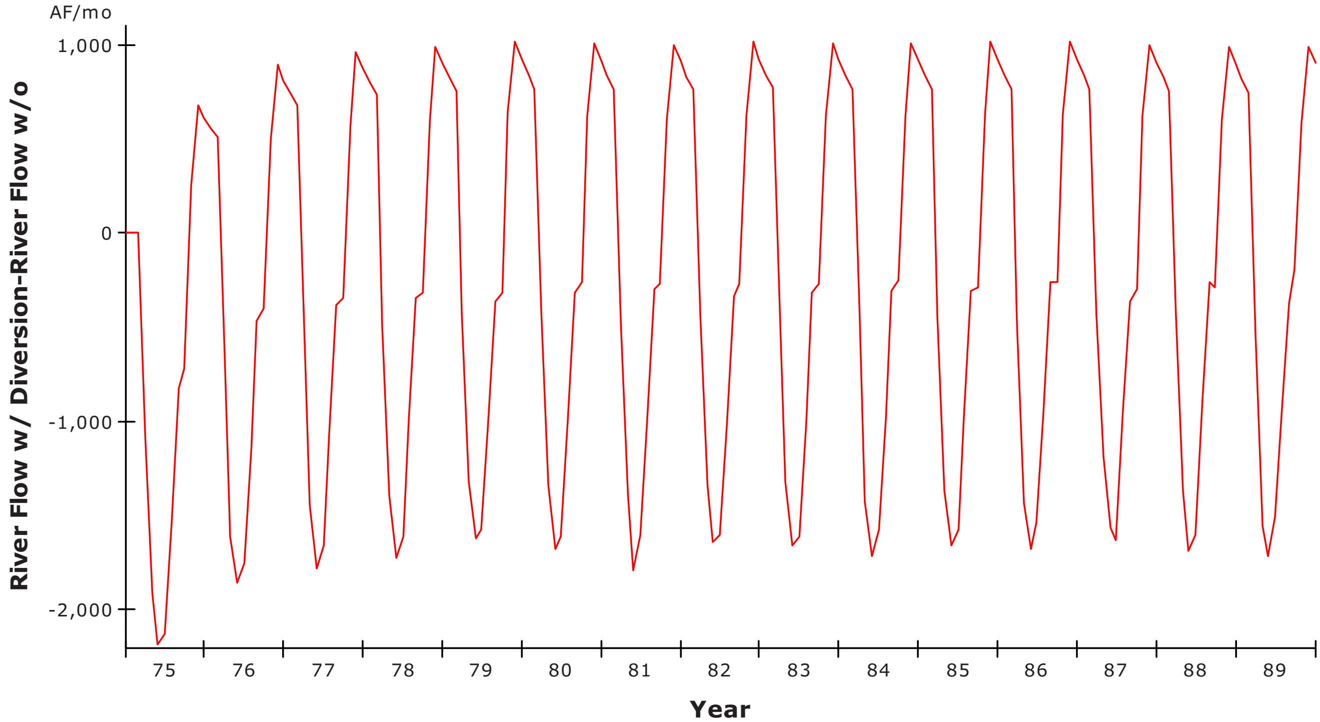

Fig. 8. Increase in winter river flow as a result of return flow from irrigation origin seepage

flow is augmented by the retransmission. In this and similar semi-arid regions with irrigated valleys fed by snowmelt, loss of traditional irrigation system seepage will lead to flashier hydrographs, exacerbating historic runoff variability and the effects of projected future climate variation shift to earlier and more rapid spring runoff. Studies in Spain and Portugal showed important groundwater recharge from acequias (Pulido-Bosch and Ben Sbih 1995; Stigter et al. 1998). Beyond groundwater recharge, this study has shown that these acequia irrigation systems dampen hydrograph flashiness and provide wet water downstream during low-flow periods.

In contrast to often perceived water waste from leaking canals and fields, seepage appears to provide multiple benefits. Maintenance and continuation of traditional irrigation practices could potentially support multiple beneficial valley floodplain functions beyond the hydrologic functions discussed above. Cool water returning underground to the river (during the warmest season and lowest river flows) may provide an important fisheries' benefit. The study valley lies in a transition zone between warm-water fisheries and cold-water fisheries. The lowest elevation to which cold-water fisheries extend is sensitive to water temperature, and the cold groundwater return flow to the river during low-flow periods may maintain and enhance cold-water fishery health. Groundwater quality has been shown to be improved by dilution of resident groundwater nutrients by low ionic concentration seepage (Helmus et al. 2009). Return flow of the same improved quality water to the river may maintain water quality for human and aquatic ecosystem functions. Water distributed across the floodplain and not used by crops helps maintain wetlands (Peck and Lovvorn 2001), and the water supports a green corridor of vegetation in a larger desert landscape. Riparian areas support up to 85% of all animal species in the southwestern United States because they spend some or all of their life cycles in riparian areas. The irrigation system-supported green corridors are expanded riparian areas (Fernald et al. 2007), and they support large-scale ecosystems of semiarid and arid regions.

Benefits of traditional irrigation systems accrue at local and regional scales. Cultures built around these traditional irrigation systems support community resource allocation particularly suited to highly variable precipitation of semiarid regions. Through water sharing, all irrigators within one acequia receive more water in wet years and less water in dry years. At the larger regional scale, storing water underground in cooler high elevation areas may serve to save water by reducing ET losses compared to scenarios with more water delivered to warmer low-elevation surface storage downstream with high evaporation. Maintaining water in low-flow periods is a valuable benefit, as illustrated by the high cost required elsewhere to desalinize surface water (Yuma), pump groundwater for river deliveries (Pecos river), or pump water to recharge ponds for baseflow augmentation (Colorado). Future policies may see public organization investment in perpetuation of traditional irrigation systems in order to maintain and enhance hydrologic, ecosystem, and cultural benefits of seepage and hydrograph retransmission functions.

The field-based results from extensive measurements in this study have laid the foundation for more detailed future analysis and broader model applications. Nearing completion is an integrated surface water and groundwater model that explicitly models the irrigation canal network coupled with a 3D groundwater model of the Alcalde Valley. Ongoing work includes refined modeling of river to floodplain to foothill surface and groundwater connections with two-dimensional and 3D models that explicitly incorporate water dynamics in the vadose zone. The hydrologic functions and water balance components characterized within the system dynamics model will serve as the basis to aggregate results over the entire middle Rio Grande basin within New Mexico. This modeling effort will improve understanding of traditional irrigation systems and surface water-groundwater connec-

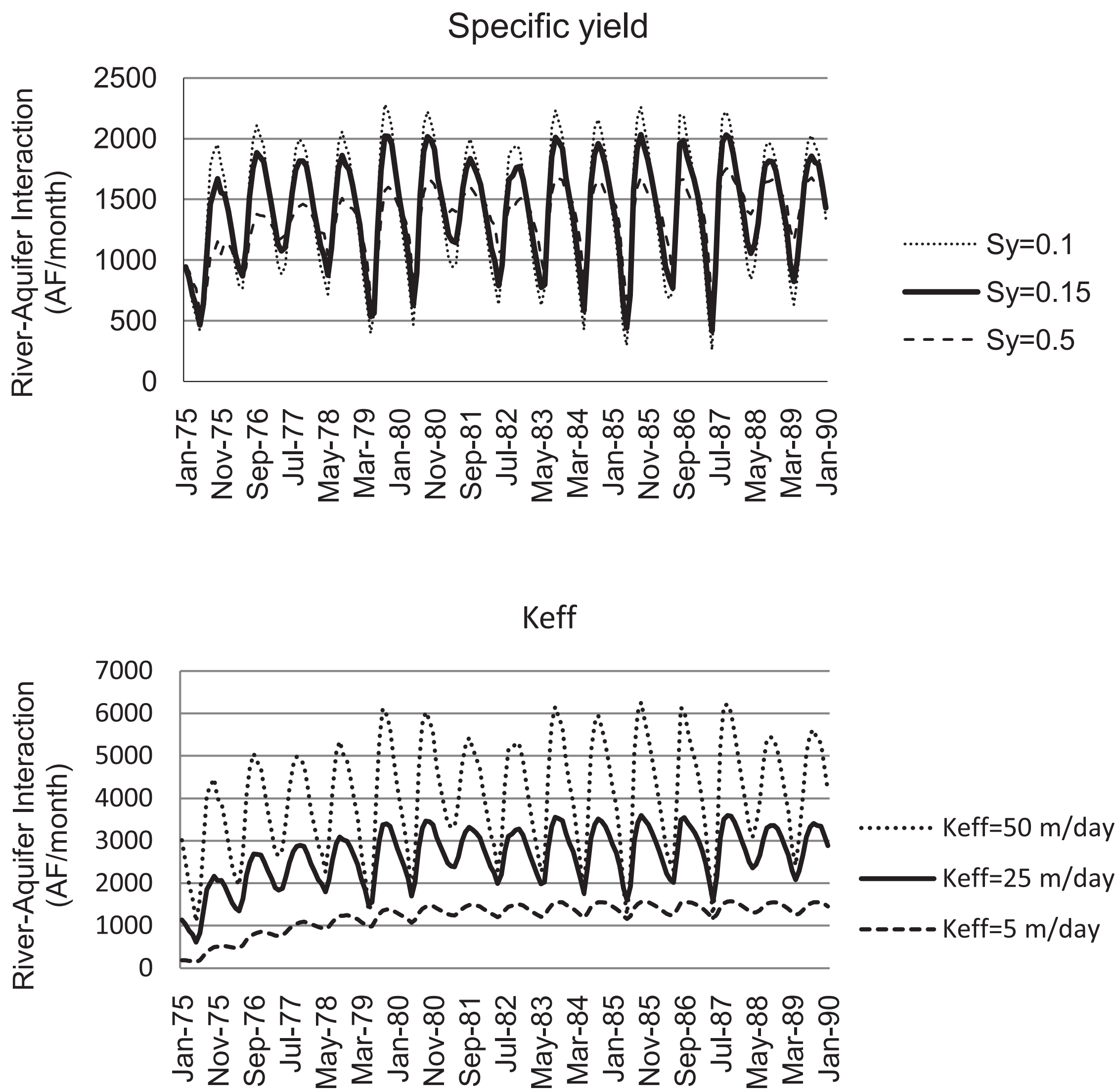

Fig. 9. Example plots from sensitivity analysis showing the one parameter. Specific yield was typical of multiple model input parameters; model seasonal response varied as specific yield inputs varied, but the mean annual response was little changed. Effective hydraulic conductivity (K_{eff}), stood as the parameter to which the model was most sensitive, with both seasonal and mean model responses varying greatly with low to high K_{eff} input values.

tion effects on river flow under scenarios of changing climate and land use.

Conclusions

This study provides previously unavailable field-based estimates of current hydrologic budgets and modeled projections of hydrologic changes under different future resource-use scenarios. Surface water-groundwater interactions greatly affect river flow in this arid region study site. Hydrologic effects of acequia irrigation are to store spring runoff and release it later. This function saves water by reducing ET. The value of saved water likely exceeds the value of all crops from cropland in these acequia-irrigated valleys where recharge and return flow are enhanced. Modeled scenarios showed that irrigation seepage results in a large amount of groundwater return flow to the river and more fall and winter river flows. Retention of the hydrologic functions of the traditional irrigation systems may prolong the river runoff hydrograph, save water via reduced ET from underground water storage compared to aboveground storage, and ameliorate effects of climate variation on local and regional water users. There is valid cause to explore private or public options to maintain, preserve, and enhance the acequia irrigation systems as they are now to preserve hydrologic functions and save water in the southwestern United States.

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References

Ahuja, L. R., Rojas, K. W., Hanson, J. D., Shaffer, M. J., and Ma, L., eds. (2000). *Root zone water quality model: Modeling management effects on water quality and crop production*, Water Resources Publications, LLC, Highland Ranch, Colo.

Alam, M. M., and Bhutta, M. N. (2004). "Comparative evaluation of canal seepage investigation techniques." *Agric. Water Manage.*, 66, 65–76.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). "Crop evapotranspiration: Guidelines for computing crop requirements." *Irrigation and Drainage Paper No. 56*, FAO, Rome.

Asare, D. K., Sitze, D. O., Monger, C. H., and Sammis, T. W. (2000). "Impact of irrigation scheduling practices on pesticide leaching at a regional level." *Agric. Water Manage.*, 43(3), 311–325.

Bexfield, L. M., and McAda, D. P. (2003). "Simulated effects of groundwater management scenarios on the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico." *USGS Open File Rep. No. 03-4040*, USGS, Albuquerque, N.M.

Borton, R. L. (1974). "General geology and groundwater conditions in the Truchas-Espanola-Velarde area of Rio Arriba County, New Mexico. New Mexico Geological Society Guidebook." *25th Field Conf.*, State Engineer Office, Santa Fe, N.M., 351–354.

Brower, A. (2008). "ET toolbox evapotranspiration toolbox for the Middle Rio Grande: A water resources decision support tool." *Bureau of Reclamation*, ⟨http://www.usbr.gov/pmts/rivers/awards/ettoolbox.pdf⟩ (Nov. 11, 2008).

Buchanan, T. J., and Somers, W. P. (1976). "Techniques of water-resources investigations of the United States Geological Survey." *Book 3: Applications of hydraulics*, 2nd Ed., Chap. A8, U.S. GPO, Washington, D.C.

Bureau of Business and Economic Research. (2008). "New Mexico County population projections July 1, 2005 to July 1, 2035." *Univ. of New Mexico*, ⟨http://www.unm.edu/~bber/demo/table2.htm⟩ (Nov. 20, 2008).

Calleros, J. R. (1991). "The impact on Mexico of the lining of the all-American canal." *Nat. Resour. J.*, 31(4), 829–838.

Carter, R. W., and Davidian, J. (1968). "General procedure for gaging streams: Applications of hydraulics." *U.S. Geological Survey techniques for water-resources investigations, book 3*, Chap. A6.

Chiew, F. H. S., and McMahon, T. A. (1991). "Groundwater recharge from rainfall and irrigation in the Campaspe river basin." *Austral. J. Soil Res.*, 29, 651–670.

de Vries, J. J., and Simmers, I. (2002). "Groundwater recharge: An overview of processes and challenges." *Hydrogeol. J.*, 10, 5–17.

Drost, B. W., Cox, S. E., and Schurr, K. M. (1997). "Changes in groundwater levels and groundwater budgets, from predevelopment to 1986, in parts of the Pasco Basin, Washington." *U.S. Dept. of the Interior/USGS Water Resources Investigation Rep. No. 96-4086*, USGS, Reston, Va.

Fernald, A. G., Baker, T. T., and Guldan, S. J. (2007). "Hydrologic, riparian, and agroecosystem functions of traditional *acequia* irrigation systems." *Journal of Sustainable Agriculture*, 30(2), 147–171.

Fernald, A. G., and Guldan, S. J. (2006). "Surface water-groundwater interactions between irrigation ditches, alluvial aquifers, and streams." *Reviews in Fisheries Science*, 14, 79–89.

Fetter, C. W. (2001). *Applied hydrogeology*, 4th Ed., Prentice-Hall, Upper Saddle River, N.J., 140–141.

Flint, A., Flint, L., Kwicklis, E., Fabrika-Martin, J., and Bodvarsson, G. (2002). "Estimating recharge at Yucca Mountain, Nevada, USA: Comparison of methods." *Hydrogeol. J.*, 10(1), 180–204.

Fox, G. A., Malone, R., Sabbagh, G. J., and Rojas, K. (2004). "Interrelationship of macropores and subsurface drainage for conservative tracer and pesticide transport." *J. Environ. Qual.*, 33, 2281–2289.

Frenzel, F. (1995). "Geohydrology and simulation of groundwater flow near Los Alamos, North-Central New Mexico." *USGS Water Resources Investigation Rep. No. 95-4091*, USGS, Albuquerque, N.M.

Garabedian, S. P. (1992). "Hydrology and digital simulation of the regional aquifer system, Eastern Snake River Plain, Idaho." *USGS Professional Paper No. 1408-F*, Reston, Va.

Gill, M. A. (1984). "Water-table rise due to infiltration from canals." *J. Hydrol.*, 70, 337–352.

Hantush, M. S. (1967). "Growth and decay of groundwater-mounds in response to uniform percolation." *Water Resour. Res.*, 3(1), 227–234.

Harvey, E. F., and Sibray, S. S. (2001). "Delineating groundwater recharge from leaking irrigation canals using water chemistry and isotopes." *Ground Water*, 39(3), 408–421.

Hawley, J. W., and Kernodle, M. (2000). "Overview of the hydrogeology and geohydrology of the northern Rio Grande Basin, Colorado, New Mexico, and Texas." *WRRI Conf. Proc.*, Water Resources Research Institute, Las Cruces, N.M., 1–23.

Healy, R. W., and Cook, P. G. (2002). "Using groundwater levels to estimate recharge." *Hydrogeol. J.*, 10, 91–109.

Hearne, G. A. (1985). "Mathematical model of the Tesuque aquifer system near Pojoaque, New Mexico." *USGS Water Supply Paper No. 2205*, USGS, Reston, Va.

Hearne, G. A., and Dewey, J. D. (1988). "Hydrologic analysis of the Rio Grande Basin north of Embudo, New Mexico, Colorado and New Mexico." *USGS Water Resources Investigations Rep. No. 86-4113*, USGS, Albuquerque, N.M.

Helmus, A. M., Fernald, A. G., VanLeeuwen, D. M., Ulery, A. L., Baker, T. T., and Abbot, L. B. (2009). "Surface water irrigation input effects on shallow groundwater quality and recharge along the Rio Grande in Northern New Mexico." *J. Am. Water Resour. Assoc.*, 45(2) 407–418.

Hunt, B., Weir, J., and Clausen, B. (2001). "A stream depletion field experiment." *Ground Water*, 39(2), 283–289.

Jaber, F. H., Shukla, S., and Srivastava, S. (2006). "Recharge, upflux and water table response for shallow water table conditions in southwest Florida." *Hydrolog. Process.*, 20, 1895–1907.

Jackson, R. B., et al. (2001). "Water in a changing world." *Ecol. Appl.*, 11(4), 1027–1045.

Jemez y Sangre Regional Water Plan. (2003). *Prepared for Jemez y Sangre Water Planning Council*, Daniel B. Stephen and Associates, Inc., Albuquerque, N.M.

Keating, H. E., Kwicklicks, E., Witkowski, M., and Ballantine, T. (1999). "A simulation model for the regional aquifer beneath the Pajarito Plateau." *Los Alamos National Laboratory Groundwater Protection Program, LA-UR-00-1029*, Soil Science Society of America, Madison, Wis.

Keating, H. E., Robinson, B. A., and Vesselinov, V. V. (2005). "Development and application of numerical models to estimate fluxes through the regional aquifer beneath the Pajarito Plateau." *Vadose Zone J.*, 4, 653–671.

Kendy, E., and Bredehoeft, J. D. (2006). "Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow." *Water Resour. Res.*, 42, W08415.

Koning, D. J., Aby, S., and Finch, S. (2007). "Where is the water?—A preliminary assessment of hydrogeologic characteristics of lithostratigraphic units near Española, north central New Mexico: New Mexico Geological Society guidebook." *58th Field Conf.*, New Mexico Geological Society, Santa Fe, N.M., 475–484.

Konrad, C. P., Drost, B. W., and Wagner, R. J. (2005). "Hydrogeology of the unconsolidated sediments, water quality, and ground-water/surface-water exchanges in the Methow River Basin, Okanogan County, Washington." *USGS Water-Resources Investigations Rep. No. 03-4244*, Version 1.1, USGS, Reston, Va.

Leaney, F. W., and Herczeg, A. L. (1995). "Regional recharge to a karst aquifer estimated from chemical and isotopic composition of diffuse and localised recharge, South Australia." *J. Hydrol.*, 164, 363–387.

Mankin, K. R., and Koelliker, J. K. (2000). "A hydrologic balance approach to saline seep remediation design." *Appl. Eng. Agric.*, 16, 129–133.

Maurer, D. K. (2002). "Ground-water flow and numerical simulation of recharge from streamflow infiltration near Pine Nut Creek, Douglas County, Nevada." *Water Resources Investigation Rep. No. 02-4145*, Carson City, Neb.

McAda, D. P., and Barrol, P. (2002). "Simulation of groundwater flow in the Middle Rio Grande Basin between Cochiti and San Acacia, New Mexico." *USGS Water Resources Investigation Rep. No. 02-4200*, USGS, Albuquerque, N.M.

McAda, D. P., and Wasiolek, M. (1988). "Simulation of the regional geohydrology of the Tesuque aquifer system near Santa Fe, New Mexico." *USGS Water Resources Investigation Rep. No. 87-4056*, USGS, Albuquerque, N.M.

Meijer, K., Boelee, E., Augustijn, D., and van der Molen, I. (2006). "Impacts of concrete lining of irrigation canals on availability of water for domestic use in southern Sri Lanka." *Agric. Water Manage.*, 83, 243–251.

Moghazi, H. E. M., and Ismail, E.-S. (1997). "A study of losses from field channels under arid region conditions." *Irrig. Sci.*, 17, 105–110.

Ochoa, C. G., Fernald, A. G., Guldan, S. J., and Shukla, M. K. (2007). "Deep percolation and its effects on shallow groundwater level rise following flood irrigation." *Trans. ASABE*, 50(1), 73–81.

Ochoa, C. G., Fernald, A. G., Guldan, S. J., and Shukla, M. K. (2009). "Water movement through a shallow vadose zone: A field irrigation experiment." *Vadose Zone J.*, 8(2), 414–425.

Office of the State Engineer—Hydrology Bureau. (2000). "Domestic wells in New Mexico—The impact of, and problems associated with domestic water wells in New Mexico." ⟨http://www.ose.state.nm.us/publications/tech_rpts/dom_wells_nm.pdf⟩ (Jan. 5, 2009).

Peck, D. E., and Lovvorn, J. R. (2001). "The importance of flood irrigation in water supply to wetlands in the Laramie Basin, Wyoming, USA." *Wetlands*, 21(3), 370–378.

Pulido-Bosch, A., and Ben Sbih, Y. (1995). "Centuries of artificial recharge on the southern edge of the Sierra Nevada (Granada, Spain)." *Environ. Geol.*, 26, 57–63.

Quinn, N. W. T., Smith, R. B., Burt, C. M., Slavin, T. S., Styles, S. W., and Mansoubi, A. (1989). "Water seepage from unlined ditches and reservoirs." *California Agriculture*, 43(6), 9–12.

Ram, S., Jaiswal, C. S., and Chauhan, H. S. (1994). "Transient water table rise with canal seepage and recharge." *J. Hydrol.*, 163, 197–202.

Roach, J., and Tidwell, V. C. (2009). "A compartmental-spatial system dynamics approach to groundwater modeling." *Ground Water*, 47(5), 686–698.

Samani, Z., and Magallanez, H. (2000). "Simple flume for flow measurement in open channel." *American Society of Civil Engineers (ASCE) Journal of Irrigation and Drainage*, 126(2), 127–129.

Sammis, T. W., Evans, D. D., and Warrick, A. W. (1982). "Comparison of methods to estimate deep percolation rates." *Water Resour. Bull., Am. Water Resour. Association*, 18(3), 465–470.

Sanford, W. (2002). "Recharge and groundwater models: An overview." *Hydrogeol. J.*, 10(1), 110–120.

Scanlon, B. R., Dutton, A., and Sophocleous, M. A. (2003). "Groundwater recharge in Texas." *Submitted to Texas Water Development Board*, Bureau of Economic Geology, The Univ. of Texas at Austin, Austin, Tex.

Scanlon, B. R., Reedy, R. C., Stonestrom, D. A., Prudic, D. E., and Dennehy, K. F. (2005). "Impact of land use and land cover change on groundwater recharge and quality in the southwestern US." *Glob. Chang. Biol.*, 11, 1577–1593.

Schmidt, K. D., and Sherman, I. (1987). "Effect of irrigation on groundwater quality in California." *J. Irrig. Drain. Eng.*, 113(1), 16–29.

Schoups, G., Addams, C. L., and Gorelick, S. M. (2005). "Multi-objective calibration of a surface water-groundwater flow model in an irrigated agricultural region: Yaqui Valley, Sonora, Mexico." *Hydrology Earth Syst. Sci.*, 9, 549–568.

Singh, R., Kroes, J. G., van Dam, J. C., and Feddes, R. A. (2006). "Distributed ecohydrological modelling to evaluate the performance of irrigation system insa district, India: I. Current water management and its productivity." *J. Hydrol.*, 329, 692–713.

Smith, R. J. (1982). "Seepage from earthen channels—A review." *Agricultural Engineering Conf.: Resources, Efficient Use and Conservation*, Institution of Engineers, Australia, National Conf. Publication No. 82/8.

Sophocleous, M. A. (1991). "Combining the soil water balance and water level fluctuation methods to estimate natural groundwater recharge—Practical aspects." *J. Hydrol.*, 124, 229–241.

Sophocleous, M. A. (2002). "Interactions between groundwater and surface water: The state of the science." *Hydrogeol. J.*, 10, 52–67.

Stephens, D. B. & Associates, and Lewis, A. (2003). *Jemez y Sangre Regional Watre Plan Volume 1: Report*, Daniel B. Stephens & Associates, Inc., Albuquerque, ⟨http://www.ose.state.nm.us/water-info/NMWaterPlanning/regions/jemezysangre/jys_sec1-5.pdf⟩ (Dec. 19, 2006).

Stigter, T. Y., van Ooijen, S. P. J., Post, V. E. A., Appelo, C. A. J., and Carvalho Dill, A. M. M. (1998). "A hydrogeological and hydrochemical explanation of the groundwater composition under irrigated land in a Mediterranean environment, Algarve, Portugal." *J. Hydrol.*, 208(3–4), 262–279.

Stonestrom, D. A., Prudic, D. E., Laczniak, R. J., Akstin, K. C., Boyd, R. A., and Henkelman, K. K. (2003). "Estimates of deep percolation beneath native vegetation, irrigated fields, and the Amargosa-River channel, Amargosa Desert, Nye County, NV." *USGS Open-File Rep. No. 2003-104*, USGS, Reston, Va.

Tidwell, V. C., Passell, H. D., Conrad, S. H., and Thomas, R. P. (2004). "System dynamics modeling for community-based water planning: An application to the Middle Rio Grande." *Journal of Aquatic Sciences*, 66, 357–372.

Upadhyaya, A., and Chauhan, H. S. (2001). "Water table fluctuations due to canal seepage and time varying recharge." *J. Hydrol.*, 244, 1–8.

USGS. (2009a). "08279500 Rio Grande at Embudo, NM, surface water daily data." *USGS, National Water Information System*, ⟨http://waterdata.usgs.gov/nwis⟩ (Sept. 12, 2009).

USGS. (2009b). "08281100 Rio Grande above San Juan Pueblo, NM, Surface water daily data." *USGS, National Water Information System*, ⟨http://waterdata.usgs.gov/nwis⟩ (Sept. 12, 2009).

Vázquez-Suñé, E., Capino, B., and Carrera, J. (2007). "Estimation of recharge from floods in disconnected stream-aquifer systems." *Ground Water*, 45(5), 579–589.

Vickers, A. (2001). *Handbook of water use and conservation*, WaterPlow Press, Amherst, Mass.

Wachyan, E., and Rushton, K. R. (1987). "Water losses from irrigation canals." *J. Hydrol.*, 92, 275–288.

Willis, T. M., and Black, A. S. (1996). "Irrigation increases groundwater recharge in the Macquarie Valley." *Austral. J. Soil Res.*, 34, 837–847.

Willis, T. M., Black, A. S., and Meyer, W. S. (1997). "Estimates of deep percolation beneath cotton in the Macquarie Valley." *Irrig. Sci.*, 17, 141–150.

Wissmar, R. C. (2004). "Riparian corridors of Eastern Oregon and Washington: Functions along lowland-arid to mountain gradients." *J. Aquatic Sciences*, 66(4), 373–387.

WRCC. (2006). "Western Regional Climate Center. Alcalde, New Mexico (290245). Period of record monthly climate summary. Period of record 04/01/1953–12/31/2005." available at ⟨http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?nmalca⟩ (Feb. 2, 2009).

Young, C. A., and Wallender, W. W. (2002). "Spatially distributed irrigation hydrology: Water balance." *Trans. ASAE*, 45(3), 609–618.

Youngs, E. G. (1977). "The unsteady groundwater mound below an irrigation ditch or leaky canal." *J. Hydrol.*, 34, 307–314.

Yussuff, S. M., Chauhan, H. S., Kumar, M., and Srivastava, V. K. (1994). "Transient canal seepage to sloping aquifer." *J. Drainage Engin.*, 120(1), 97–109.

Zektser, S., Loáiciga, H. A., and Wolf, J. T. (2005). "Environmental impacts of groundwater overdraft: Selected case studies in the southwestern United States." *Environ. Geol.*, 47, 396–404.