Hydrologic, Riparian, and Agroecosystem Functions of Traditional *Acequia* Irrigation Systems

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ABSTRACT. Traditional cultures in arid landscapes of the southwestern United States and northern Mexico developed irrigation systems to irrigate floodplain valleys along streams and rivers. Many of these traditional irrigation systems, referred to as *acequias*, continue to be used today. Population growth in the region is creating pressures to convert agricultural land and irrigation water to urban and other uses. Unique hydrologic features of the *acequia* systems suggest that, beyond provid-

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ing crop irrigation, they may provide additional valuable hydrologic, riparian, and agroecosystem functions worth maintaining. We investigated in detail the seepage and the groundwater response to seepage from a traditional *acequia* irrigation ditch along the Rio Grande in north-central New Mexico. We found that 16% of ditch flow seeps into the ditch bed and banks. Groundwater levels near the ditch and midway between the ditch and the river rise 1 m or more within three to four weeks following the start of the irrigation season. The elevated groundwater table produced by ditch and field seepage is sustained until late summer when groundwater levels again drop. The seepage that provides this annual groundwater recharge also sustains riparian vegetation along the main ditch and side ditches. In light of our hydrologic analysis, we considered seepage-supported riparian areas and their ecological functions including aquatic habitat, terrestrial habitat, and water quality effects. *Acequia* hydrology plays an important role in contributing to an ecologically healthy, agriculturally productive, and community-sustaining floodplain agroecosystem. doi:10.1300/J064v30n02_13 *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <http://www.HaworthPress.com>*

KEYWORDS. *Acequia*, agroecosystem, ecosystem services, hydrology, irrigation, multifunctional agriculture, riparian, seepage

INTRODUCTION

Multifunctional agriculture is an emerging theme in agricultural research (Boody et al., 2005; Brandt, 2003; Dobbs, 2004; Vereijken, 2002), and the term ecosystem services addresses similar themes in the natural science literature (Daily, 1997; Holechek et al., 2001; Strange et al., 1999). Multifunctional agriculture and ecosystem services are terms applied to the concept that agriculture provides a number of functions, benefits, and services beyond the production of food, fiber, fuel, and industrial products (Daily, 1997; Dobbs, 2004; Francis et al., 2004; Holechek et al., 2001; OECD, 2001). The multiple functions or benefits of agricultural pursuits have been an important topic in world agricultural trade negotiations (DeVries, 2000). From a natural science point of view, the ecosystem services provided by agricultural systems provide an ideal framework upon which to develop a greater understanding of agroecosystems and their impacts on natural resources and society.

By seeking to understand the ways in which agricultural practices potentially provide additional secondary benefits or services to society and the environment, the multifunctional agriculture approach complements general sustainable agriculture goals of providing adequate production while minimizing negative effects on the environment and natural resource base. This approach has the potential to contribute to a better understanding of management practices that further the goals of enhancing agricultural sustainability and agroecosystem integrity. This approach is important for illustrating the full or potential value that agriculture can provide from both social and ecological perspectives. This understanding at local and regional scales is important for agriculturists, natural resource scientists, natural resource economists, policy makers, resource managers, and the general public.

Assessing ecosystem services provided by agriculture could be critical in locations where there are pressures to convert agricultural land and water resources to other uses that are viewed as having a higher value. Farmers throughout the southwestern United States are increasingly facing these pressures. Traditional agricultural properties and irrigation water are being rapidly converted to urban and other uses. As in other parts of the country, farmers in the region are increasingly being urged to develop and utilize more efficient irrigation strategies. In this context, efficiency generally means using less water for agriculture and providing more for municipal and industrial uses. These pressures have been exacerbated by recent droughts and the perception that water used to irrigate agricultural fields is lost to the overall water budget. Counter to these perceptions, we forward the concept that water from irrigation systems may support many important hydrologic and ecological functions beyond watering crops. This support of additional ecosystem processes may be particularly true for traditional irrigation ditches and flood irrigation along streams and rivers of the Southwest.

Development of agriculture in arid and semiarid regions of North America led to a wide variety of agricultural systems. Over time, indigenous peoples selected crop types appropriate for their local climate (Dunmire, 2004). In addition, various water harvesting and stream diversion techniques were developed to provide sufficient and reliable water distribution, reduce risk of crop loss, and increase crop yields (Doolittle, 1995; Dunmire, 2004). At one site in the floodplain of the Santa Cruz River in Arizona, archaeologists found evidence that irrigation canals existed by about 1200-1100 B.C. (Mabry, 1999). When the region that is now the southwestern United States and north central Mexico was colonized under Spanish rule beginning in the sixteenth century, irrigated agriculture was greatly expanded through development of extensive networks of irrigation ditches called *acequias* (Cech, 2005; Rivera, 1998).

Acequias divert water away from the supplying river or stream to allow gravity-fed irrigation in the downstream floodplain corridor between the *acequia* and the river. Most ditches run during the irrigation season, which coincides with the growing season, or as long as water is available from the supplying watercourse. They continue to be used by small-scale farmers and ranchers throughout the region. In New Mexico alone, the Office of the State Engineer (OSE) estimates there are about 800 community *acequia* and ditch associations (OSE, 1997). Pressures to change *acequia* irrigation systems may alter ecological functions of and the ecosystem services provided by the irrigated landscape by transforming underlying hydrology that supports many of these functions. Because *acequias* often flow continuously during the irrigation season and have potentially high flow losses due to seepage from earthen beds and banks, methods have been proposed to improve their water delivery and efficiency of use. These methods include lining earthen ditches with impermeable materials to prevent seepage, replacing *acequias* with pipe, and irrigating with low-volume application equipment. Although lining and piping have been appropriately used in certain situations, broad-scale conversions away from traditional *acequia* irrigation systems are expensive, particularly over the extensive areas that currently employ traditional methods. These conversions also present a departure from long-standing customs and culture present in the region, and may have the potential to significantly alter ecological processes in these landscapes. The driving force behind many ecological functions is the hydrologic interaction between surface water and groundwater in the floodplain corridor between irrigation ditches and the supplying watercourse.

Studies of the hydrologic effects of seepage from irrigation ditches have shown that ditch seepage is an important source of recharge to shallow groundwater and may provide groundwater return flow to the river along with important water quality effects on groundwater and the river. Harvey and Sibray (2001) concluded that irrigation ditch seepage caused a rise in local groundwater levels and Maurer (2002) suggested that seepage caused groundwater mounds that dissipated when ditch seepage stopped. Comparing side-by-side systems where unlined ditches had 60 times greater seepage than lined ditches, seepage from unlined ditches dramatically increased groundwater flows and caused elevated water tables compared with the lined ditch system (Drost et al., 1997).

In another study, lining irrigation ditches reduced the availability of shallow groundwater that supplied wells to irrigate associated cropland (Calleros, 1991). The shallow groundwater flow caused by ditch seepage may dilute contaminants in shallow groundwater and protect deeper groundwater quality by transporting contaminants away from the deeper aquifer. If lining ditches reduces seepage rates, there may be less recharge to shallow groundwater, and in turn, less groundwater return flow to the river. On the other hand, unlined ditches provide seepage that may augment groundwater return flow to the river. A study of the Methow River Valley in Washington showed that shallow groundwater return flow from ditch and field seepage provided 20% of the mean September baseflow (Konrad et al., 2003), and irrigation seepage was important for connectivity between the floodplain and the river (Wissmar, 2004). In places where previously active meandering and braided river channels have been constrained and simplified by man-made structures, ditch and flood irrigation seepage that recharges shallow groundwater and returns as subsurface flow to the river may store a portion of runoff from peak river flow periods and release it during lower flow periods. Thus the irrigation seepage may be performing some hydrologic functions previously performed by floodplain relict side channel features.

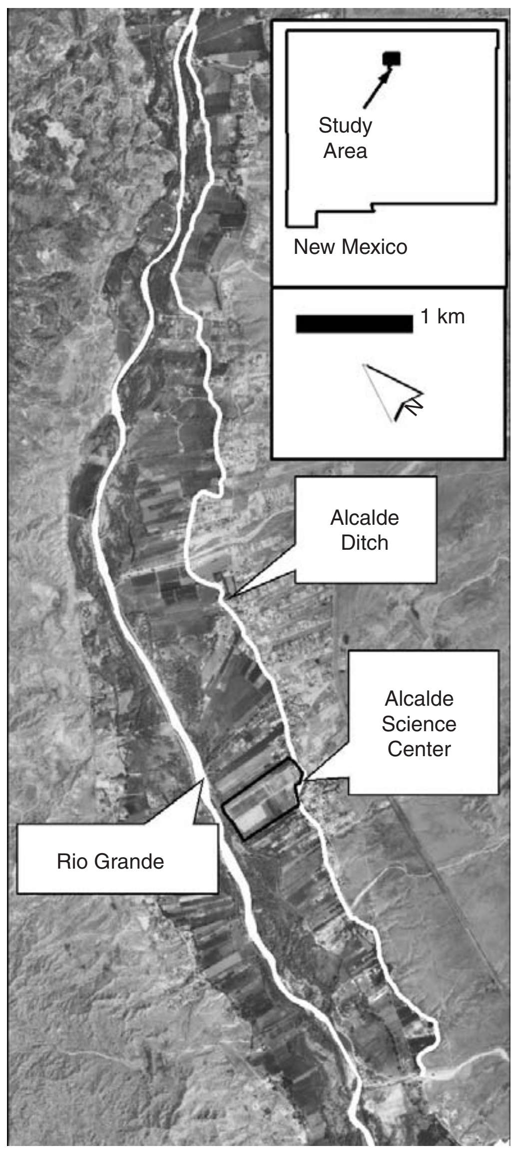
Components of *acequia*-irrigated agricultural systems have some functional resemblance to natural riparian systems of the region. Riparian areas are transition zones and areas of direct interactions between aquatic and upland environments. The materials, energy, and organisms that are transferred between these two environments affect and are affected by a vegetation community that is compositionally, structurally, and functionally distinct from upslope vegetation communities (Swanson et al., 1982; Waring and Schlesinger, 1985). Hydrologic processes, occurring as flooding above the soil surface and groundwater flow below the soil surface, govern vegetation transitions between aquatic and upland environments in the Southwest. While riparian areas are apparent and distinctive in the arid Southwest compared with their counterparts in more mesic environments, they are also more spatially limited. In the arid southwestern United States, riparian areas occupy an extremely small portion of the overall landscape, less than 2% according to some sources (Szaro, 1989). However, the ecological importance of riparian areas far outweighs their spatial representation in that landscape. Cartron et al. (2000) listed over 125 species of birds that nested in riparian areas or wetlands in the Southwest. Hubbard (1977) estimated that riparian habitats supported 42% of the mammals, 38% of the birds, 33% of the reptiles, and 13% of the amphibians in the arid West. Riparian areas, through their vegetative components, are also responsible for attenuating floodwater damage, filtering contaminants, maintaining bank stability, providing a source point for recharging groundwater, and protecting water quality (DeBano and Schmidt, 1989). Historic floodplains are the site of many present-day agricultural fields, where producers take advantage of the productive alluvial soils and where *acequia* irrigation maintains a belt of green vegetation that appears much like a band of riparian vegetation within the larger arid landscape.

A more thorough understanding of hydrologic, ecological, and agroecological implications of significantly altering *acequia* irrigation systems is critically important for farmers, natural resource managers, and the general public. To improve this understanding, we conducted a field study to examine hydrologic functions in an *acequia*-irrigated agricultural landscape in northern New Mexico. The objective of our field research was to characterize hydrologic processes in the irrigated floodplain with particular emphasis on the interactions between irrigation seepage and shallow groundwater. In this paper, we use the hydrologic field study results as a springboard from which to explore multiple ecological functions served by riparian communities associated with flood-irrigated agriculture. In addition, we assess potential effects of future land and water use changes on irrigated floodplain ecological services.

MATERIALS AND METHODS

Field research was conducted in alluvial croplands along a river valley representative of many sites throughout the semiarid western United States. Most field measurements were taken at New Mexico State University's Alcalde Sustainable Agriculture Science Center (Alcalde Science Center) in north-central New Mexico, which occupies almost the entire width of irrigated corridor between the Alcalde Ditch and the Rio Grande (Figure 1). The Alcalde Science Center has 24 ha of land mostly irrigated by surface flood or furrow irrigation, by far the most common practices in the valley and region. Crops grown at the Alcalde Science Center are typical of those grown on irrigated land in the region: Alfalfa, pasture grasses, apples, chile, sweet corn, and other specialty crops. Soils at the Alcalde Science Center include Fruitland sandy loam, Werlog clay loam, and Alcalde clay. These are typical of the range of soils found locally.

FIGURE 1. Irrigated corridor study area along the Rio Grande illustrating darker color irrigated croplands in the center bounded by lighter color non-irrigated lands on the east and west.



Data were also collected outside the bounds of the Alcalde Science Center along the length of the Alcalde Ditch, a traditional *acequia* (Figure 1). The mostly unlined Alcalde Ditch is 9200 m long between the intake diversion structure and the tail end return flow outlet into an existing ephemeral wash. For most of its length the Alcalde Ditch is the only irrigation ditch on the east side of the Rio Grande, delineating the boundary between irrigated lands to the west and non-irrigated rangelands and housing areas to the east. The Alcalde Ditch is typical of irrigation ditches in the region, with river flow diverted into it throughout the March to October irrigation season to supply water to individual private farms along the length of the ditch. A control structure 1.3 km from the river intake regulates average flow in the ditch, which ranges from 0.69 to 0.86 m^3 s^{-1} under normal operating conditions. Unused ditch flow is returned to the river at the tail end of the ditch. A reliable water source for the Alcalde Ditch is provided by the Rio Grande, which has late summer and early fall low flow of at least 4 m^3 s^{-1}. Snowmelt generates a two- to four-month spring runoff period with highest recorded average monthly flow in May of 67 m^3 s^{-1} at the upstream Embudo Station (USGS, 2006). Yearly instantaneous peak flow averaged 139 m^3 s^{-1} over a 116-year period of record at Embudo Station, occurring most often from April to June, but generated in 16% of years from July to September during the summer monsoon season. Riparian vegetation along the banks of the river and larger irrigation ditches is composed primarily of Siberian elm and phreatophytic tree species such as willow, cottonwood, and Russian olive. Some notable differences between river-side and ditch-side riparian vegetation may be in structure and extent. The close proximity of the groundwater table, the topographical relief (i.e., swales), and the lack of cultivation adjacent to the river permit a more expansive, and perhaps diverse, community adjacent to the river. This study site is ideal to investigate surface water-groundwater interactions and riparian vegetation communities in the agricultural lands spanning the irrigated corridor from an irrigation ditch to a major river, and overlying a shallow alluvial aquifer.

For study of irrigation ditch seepage effects on surface water-groundwater interactions along the Rio Grande river corridor, we installed instrumentation at the Alcalde Science Center beginning in late 2001. Estimates of ditch seepage were made for the Alcalde Science Center portion of the ditch using impoundment tests and for the entire irrigated length of the ditch using inflow-outflow comparison. In 2002 and 2003, ditch seepage rates were measured in impoundments over a 60 m length of earthen ditch and a 40 m length of stone-bank ditch at the Alcalde

Science Center. Steady state ditch inflow-outflow measurements were taken in November 2004 after the irrigation season when there were no observed irrigation diversions from the ditch. The measurement locations were at the upstream and downstream ends of the active irrigation supply portion of the Alcalde Ditch, which had no flow inputs other than the main river diversion. Stage height in the ditch was measured hourly during the inflow-outflow test, and a rating curve was constructed to calculate ditch flow ($m^3\ s^{-1}$) from stage (m). In addition, ditch stage was measured weekly at the Alcalde Science Center.

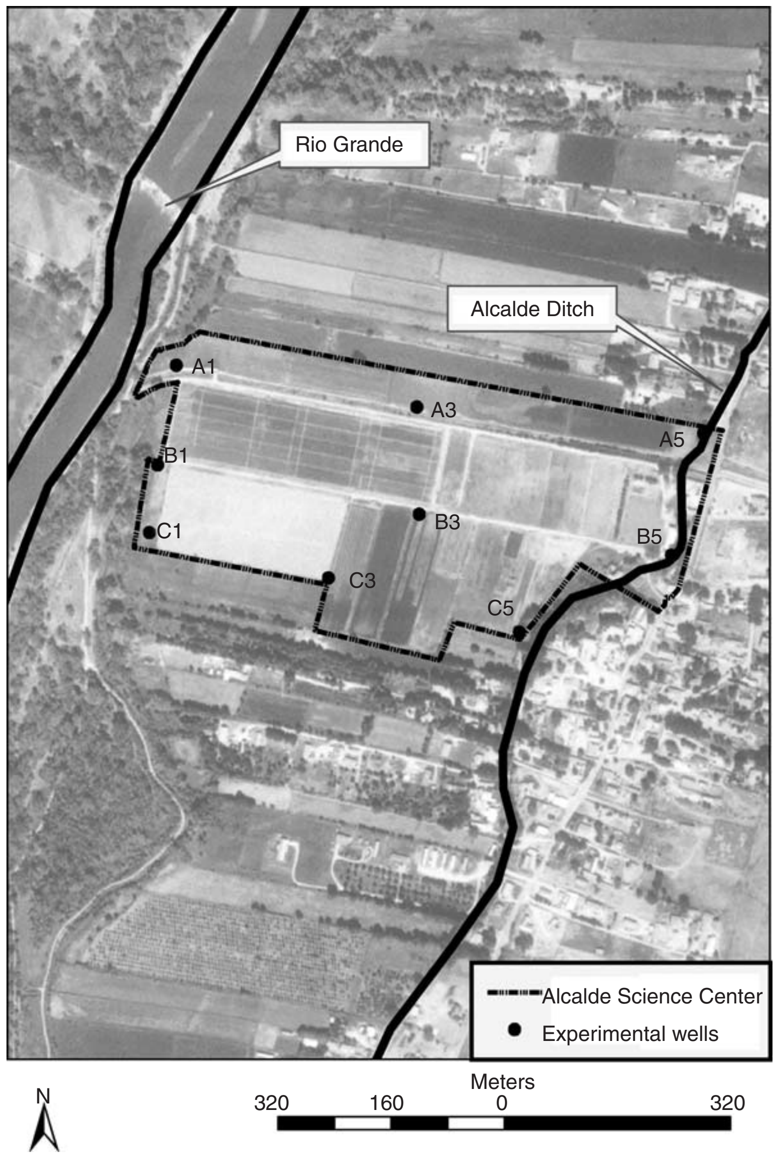
In 2002, we installed three transects of 2″ PVC (polyvinyl chloride) wells (Figure 2), each with a 1.5 m solid pipe riser above a machine-slotted well screen extending from the riser down to about 4 m below the water table at the time of installation in winter. We measured water levels weekly beginning in 2002 with a 2 mm precision Durham Geo Slope Indicator WLI® (Durham Geo Slope Indicator; Stone Mountain, GA) electronic water level indicator. To measure specific conductance (μS/cm) in the field, each well was purged for about 3 minutes until water ran clear. After waiting about 2 minutes for each well to recharge, six specific conductance data points were collected at 12 second intervals with a YSI 600XLM® (SonTek/YSI, Inc.; San Diego, CA) water quality probe and averaged to yield final specific conductance values.

We used Surfer 8® (Golden Software, Inc.; Golden, CO) three-dimensional mapping software to spatially average point water level measurements and generate potentiometric surface maps. With these depictions of the water surface in the shallow groundwater, we calculated groundwater flow path directions based on the steepest downslope gradient. We characterized the timing of groundwater response to ditch seepage with time series of ditch flow and potentiometric surface maps. To compare seasonal variations in the shallow groundwater response, we analyzed all water level readings along individual transects. With all weekly water level readings from 2002-2005, we created plots of water level data including ditch, near-ditch well, mid-field well, near-river well, and river locations.

FIELD STUDY RESULTS

Impoundment seepage rates were 11.9 cm/day from the stone-bank ditch and 10.7 cm/day from the earthen ditch, yielding an average seepage rate at the Alcalde Science Center of 11.3 cm/day. For the width,

FIGURE 2. Alcalde Science Center experimental wells.



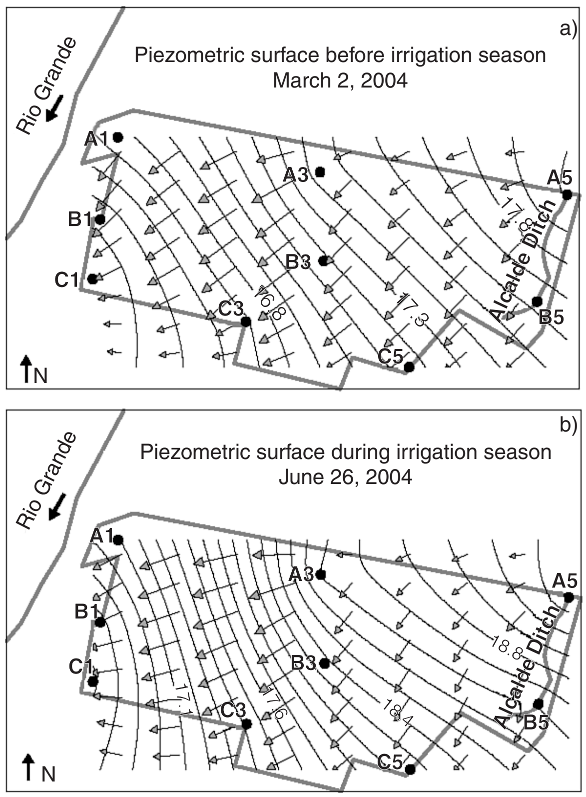
depth, and flow through the Alcalde Ditch, this seepage rate represented at least 5% of total ditch flow through the Alcalde Science Center. Our steady-state inflow-outflow measurements provided an estimate of seepage over the entire length of the ditch. Measurement of 1.54 $m^3 s^{-1}$ inflow and 1.29 $m^3 s^{-1}$ outflow showed that 16% of ditch flow escaped through the ditch bed and banks as seepage during the 5 h steady flow period during our test in autumn. Different substrates, slopes, and ditch channel morphologies likely all contributed to the higher seepage rate over the entire ditch compared with the lower seepage rate using impoundment tests at the Alcalde Science Center.

With maps of the potentiometric surface before and during the irrigation season, we documented rapid response of shallow groundwater levels to seepage. In March 2004, prior to the start of irrigation ditch flow, groundwater flow paths were oriented slightly towards the river and down the valley (Figure 3). We found that the shallow groundwater table responded to seepage from the irrigation ditch within 1 to 2 weeks of the onset of ditch flow. Thirteen weeks after the beginning of irrigation ditch flow, groundwater levels had risen 1.2 m near the ditch, and the groundwater flow paths nearer the river had oriented more towards the river (Figures 2 and 3).

In general, specific conductance of the shallow groundwater acted as a rudimentary tracer. For data from one transect (A) from July 2003 to May 2004 during times the ditch was flowing, specific conductance of ditch water (mean = 285 μS/cm) closely matched that of river water (mean = 294 μS/cm), and both were lower than groundwater (mean of three wells = 618 μS/cm). Specific conductance was 465 μS/cm in the well nearest the ditch just prior to the end of ditch flow in December. When ditch flows were turned off, specific conductance increased to 569 μS/cm in February and 646 μS/cm in March. With the resumption of ditch flow, specific conductance decreased again to 475 μS/cm by May. A similar pattern was seen in the other two well transects. These specific conductance data along with preliminary data from automatic recording conductivity meters indicate ditch seepage reached shallow groundwater and diluted higher conductivity groundwater with lower conductivity irrigation water.

Analysis of groundwater levels over time illustrates interactions between ditch seepage, field seepage, river stage, and possibly riparian vegetation evapotranspiration. After the initiation of ditch flow in the spring each year, shallow groundwater levels in well A5 (nearest the ditch) and well A3 (in the middle of the irrigated corridor) increased

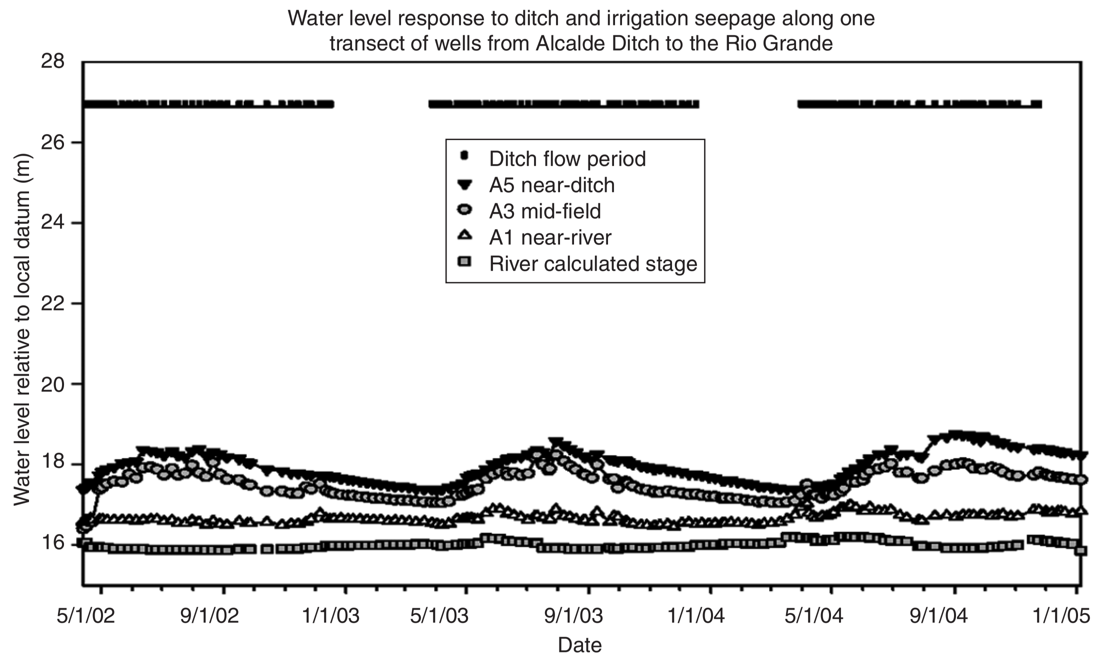
FIGURE 3. Piezometric surface and shallow groundwater flow directions at the Alcalde Center estimated from water levels in three transects (A,B,C) of three wells each (1,3,5). Figure 3a shows off-irrigation season conditions prior to the March 24 start of irrigation ditch flow. Figure 3b shows conditions thirteen weeks after irrigation ditch flow began.



until August or September, showing the movement of ditch seepage and possibly flood irrigation seepage into the irrigated corridor groundwater (Figure 4).

Before the study, our conjecture was that seepage below crops during flood irrigation would be a small hydrologic flux compared with the constant seepage from the flowing Alcalde Ditch. We observed rapid localized short-term increases in summer groundwater levels that corresponded to flood irrigation events (Figure 4), indicating that flood

FIGURE 4. Water levels in the Alcalde Ditch, three wells (A5, A3, A1), and the Rio Grande 2002-2005. Ditch water level is the average irrigation season water surface elevation. River stage was calculated using a linear regression model developed with 16 years of data from two nearby USGS gauging stations.



irrigation water seeps below the rooting zone and reaches shallow groundwater. A companion study begun in 2005 showed that 25 to 60% of applied flood irrigation water percolated below the rooting zone of alfalfa in a sandy loam soil, and within 1 day of irrigation shallow groundwater levels rose in response to seepage from the irrigation event (Ochoa, 2006).

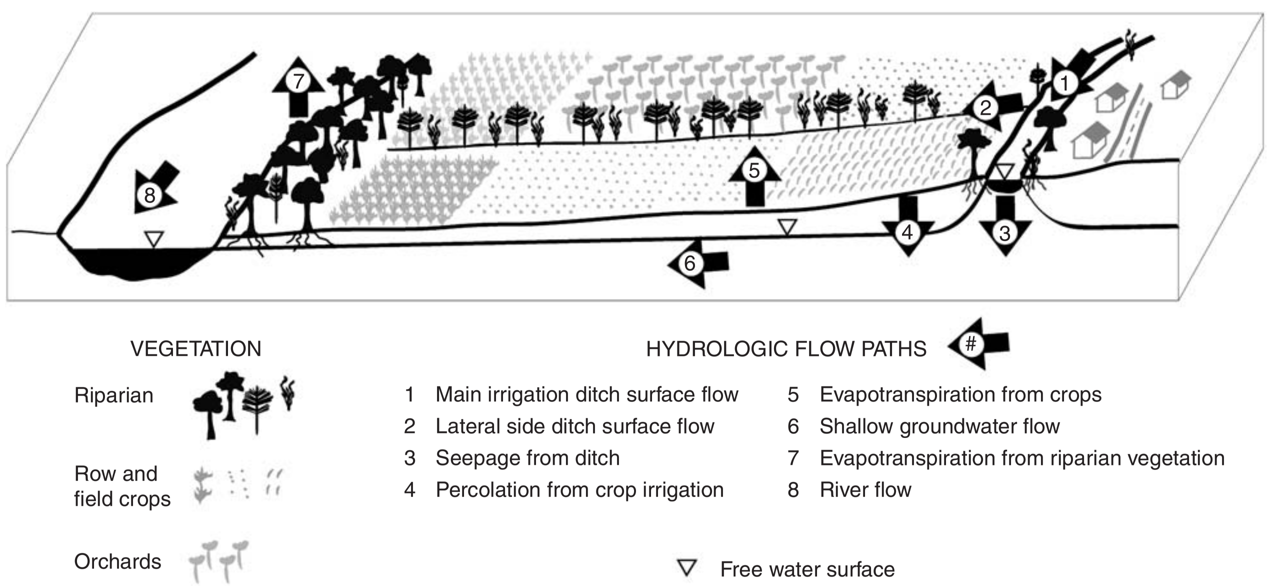
Shallow groundwater nearer the river exhibits patterns consistent with rapid interaction with the river. At the well closest to the river (well A1), there were small increases in water levels that mirrored increased river-water levels during spring runoff (Figure 4). The subsequent decreased water levels in well A1 show effects of river interaction with near-river shallow groundwater as the river-water levels dropped later in the season. The near-river groundwater may also be drawn down by riparian evapotranspiration when plants are in full leaf and early season soil water has been extracted, leading to greater extraction of riparian groundwater.

DISCUSSION

Floodplain Hydrologic Processes Maintained by Irrigation Seepage in Irrigated Agricultural Corridors. Results from our field study illustrate that seepage to shallow groundwater from *acequia* irrigation maintains floodplain hydrologic flow paths important to multiple ecological services of the irrigated agricultural corridor (Figure 5). We documented that up to 16% of total flow passing through the Alcalde Ditch seeps out of the bed and banks of the ditch. In this respect, the main ditch and side ditches that supply field irrigation resemble a braided stream network similar to the side channels present in an actively reworked floodplain. Our water table elevation data show that the Alcalde Ditch is perched above the resident valley groundwater. Seepage from the main and side ditches maintains a wetted soil profile that supports the thin strips of riparian vegetation we observed along the ditch banks.

Seepage from ditches and flood irrigated fields performs the important function of recharging shallow groundwater. Flood irrigation provides standing water on the floodplain similar to historical flooding during river peak discharge periods during spring snowmelt or large storm events. Up to 60% of flood irrigation applications percolate below the rooting zone, and this field percolation in combination with ditch seepage leads to an increase in groundwater levels during the irrigation season. Close to the river, groundwater elevations within about 1 m of the soil surface

FIGURE 5. Hydrologic flow paths in an *acequia*-irrigated alluvial floodplain.



maintain, in many places, extensive riparian forests compared with the typical one-tree-wide riparian vegetation strips along the irrigation ditches (Figure 5). Hydrologically, evapotranspiration from riparian vegetation is a significant source of groundwater withdrawal along rivers in semiarid regions (Dahm et al., 2002). Some of the most important riparian ecosystem processes supported by *acequia* systems are discussed in detail in the following discussion section.

Acequia system seepage recharge to shallow groundwater affects return flow to the river and likely changes the timing of the river hydrograph. Continual *acequia* diversion from the river during spring and summer takes a portion of high flow discharge and distributes it across the irrigated corridor. This water seeps to shallow groundwater, and on estimated timescales of four to twelve weeks, the augmented shallow groundwater returns as subsurface return flow to the river (Figures 4 and 5). The resultant augmentation of late summer and early fall river flow with early season water diverted and routed through shallow groundwater is an important hydrologic service. In a recent effort, the state of Colorado is spending large amounts of money to recharge ponds with shallow aquifer water pumped during spring runoff to provide late summer flow through groundwater return flow in the South Platte River (Durnford et al., 2006). This process is being performed over extensive areas by the traditional *acequias* in northern New Mexico without the cost of pumping. Streamside riparian vegetation may intercept groundwater return flow (Winter et al., 1998), with the evapotranspiration itself causing fluctuations in river flow (Nyholm et al., 2003). Ongoing research along the Alcalde Ditch is designed to characterize seepage, groundwater recharge, and riparian evapotranspiration to determine the amount of seepage that returns as shallow groundwater return flow to the river.

In periods when shallow groundwater return flow constitutes a relatively large proportion of river discharge, the return flow may have important effects on physical and chemical water quality in the river. Of great interest in agricultural landscapes is the ability of surface water–groundwater exchange to create conditions for denitrification and to remove nitrate from surface water and groundwater (Pinay and Decamps, 1988; Sjodin et al., 1997). The loss of irrigation seepage and groundwater recharge caused by lining canals can lead to less dilution by groundwater recharge and increased groundwater nitrate concentrations (Drost et al., 1997). Along the Alcalde Ditch, preliminary measurements indicate that ditch seepage dilutes resident shallow groundwater and reduces concentrations of constituents such as nitrate (Helmus, 2006). Stream temperatures can be cooled by the inputs of cool alluvial aquifer return flows provided by irrigation seepage (Stringham et al., 1998). Cooling provided by return flow to the Rio Grande is likely of particular importance in late summer when ambient temperatures are high and cool groundwater return flow makes up a larger proportion of river flow.

Functional Similarities Between Acequia-Irrigated Agricultural Landscapes and Riparian Ecosystems in Northern New Mexico and Throughout the Southwestern United States. We identified hydrologic processes of *acequia*-irrigated agriculture that are similar to natural riparian systems. As mentioned earlier, the complex network of earthen irrigation and drainage ditches functionally resembles a complex system of stream channels. The seepage these ditches provide to the floodplain supports riparian vegetation communities along the ditch lengths beyond the river banks. The flood irrigation process approximates overbank flooding under natural river hydrographs. These features, and their functional resemblance to natural floodplain riparian landscapes, are discussed in greater detail later in the context of riparian ecology and floodplain hydrology.

Riparian areas serve numerous important ecological functions that can be combined into categories dedicated to aquatic and terrestrial wildlife functions and soil and water conservation functions (Table 1).

TABLE 1. List of ecological functions served by riparian areas.

Water Quality
Filter sediment, fertilizers, pesticides, and other organic contaminants
Maintain streambank stability and reduce erosion
Slow floodwaters and promote sediment deposition
Increase infiltration and increase groundwater storage
Soil Conservation
Maintain streambank stability and reduce erosion
Slow floodwaters and promote sediment deposition
Terrestrial Wildlife
Provide source of water
Give shelter/refuge
Provide travel corridors
Increase forage productivity, diversity, and nutritional value
Aquatic Wildlife
Filter sediment, fertilizers, pesticides, and other organic contaminants
Maintain streambank stability and reduce erosion
Provide source of carbon, nutrients, and substrate for food chain
Shade streams

These functions appear not only at site-specific, micro-site levels but also occur at the landscape level. Riparian zones support compositionally, structurally, and functionally distinct vegetation communities that are important to numerous terrestrial wildlife species (Johnson et al., 1977; Naiman et al., 1993; Severson and Urness, 1994). Field observations along the Alcalde Ditch and in the larger surrounding valley revealed a mosaic of riparian habitats associated with the complex water distribution features of the *acequia* irrigation system. Seepage from the larger main ditches and smaller lateral ditches supports thin riparian vegetation strips along the ditch banks. Surface water inputs from the ditches, irrigated fields, and the river contribute to elevated water tables and support larger stands of phreatophytic riparian vegetation. The *acequia* system provides a valuable service to farmers for crop irrigation while simultaneously supporting riparian habitat, potentially including many important wildlife functions. This is particularly true for species that rely on *acequia*-associated riparian vegetation for nesting habitat, cover, and refuge and the adjacent agricultural crops for foraging.

Riparian zones also provide a buffer between aquatic environments and activities that occur throughout watersheds. Sediments, fertilizers, and other potential contaminants originating from upland areas within a watershed are often transported to riparian areas, where dense vegetation traps materials and immobilizes potential aquatic contaminants through vegetation uptake or in the soil column (Lowrance et al., 1984; Lowrance et al., 1985). Dense riparian vegetation also develops extensive root mats that hold soil and streambanks together during not only base-flow runoff but also high-flow events that would otherwise erode floodplains and streambanks (Beschta and Platts, 1986; Heede, 1980). Riparian vegetation along *acequias* helps to maintain irrigation ditch bank stability, reduce erosion, and provide deep perennial root systems that aid in immobilization of potential aquatic contaminants.

High water flows that access floodplains maintain natural processes beneficial to many riparian functions. There are also similarities between flood irrigation processes and riparian hydrology. In overbank flooding events, dense riparian vegetation effectively slows floodwaters and thereby promotes deposition of sediments carried in floodwater. As a result, floodplains are continuously rebuilt and aggraded as opposed to eroded away with high-flow events. Sediments that may be rich in nutrients are thereby contained within the terrestrial riparian environment where nutrients are utilized by local vegetation and contribute to high vegetative productivity within the riparian environment (Meehan and Platts, 1978; Platts, 1991). Without riparian vegetation protection, sediment and the nutrients it carries would be more likely to be carried downstream, contributing to turbidity in streamflow, excessive sediment deposition to downstream aquatic habitats, and potential eutrophication of aquatic habitats. Slowing floodwater on the floodplain also promotes infiltration of water belowground and favors groundwater recharge (DeBano and Schmidt, 1989). Therefore, water remains within a watershed for a longer period of time to be used not only by vegetation, wildlife, and for other ecological purposes, but also for human use, rather than sending water rapidly downstream to other systems for other uses. Diversion of water through *acequias* in a channelized river system such as the Rio Grande in the vicinity of this study area ensures the usage of that water throughout the floodplain and increases the residence time of water in the watershed. Annual water allocation to agricultural crops is approximately 3 acre feet of surface water applied by irrigating fields every 1 to 4 weeks throughout the growing season. In unmanaged landscapes this process occurs during the early spring months following snowmelt and following high rainfall events during the growing season; however, in the regulated and channelized river systems common throughout the Southwest, overbank flooding is virtually non-existent. While agricultural crops are flooded more frequently throughout the growing season than would be expected in an unregulated riparian environment, flood irrigation can carry nutrient-rich sediment to the floodplain thereby resembling the aggradation and nutrient-cycling functions. In fact, flood irrigation has been used as a means of seed dispersal to re-establish native cottonwood and willow communities along the Rio Grande in the Bosque del Apache National Wildlife Refuge farther south.

Significant compositional and structural differences exist between agricultural crop fields and natural riparian areas. Natural riparian areas exhibit a wide array of plant species ranging from herbaceous, ground-level plants (e.g., sedges, rushes, and a variety of annual forbs and perennial grasses) to midstory shrubs (e.g., willow and alder) up to several meters high and finally trees in the overstory (e.g., boxelder and cottonwood) with the potential of reaching several dozens of meters in height. Such compositional and structural diversity is atypical of many agricultural fields where single-species crops like alfalfa often dominate individual fields to heights on the order of 1 meter. However, other flood-irrigated agricultural fields include taller crops such as corn up to 3 m in height and fruit orchards that may reach 6 or 7 m in height. Other fields include shrub-like plants such as chile or herbaceous surface vegetation such as herbs and leaf vegetables. These fields are surrounded by irrigation and drainage ditches supporting narrow belts of riparian vegetation. At a landscape scale, this mosaic of species and structural diversity combined with the process of flood irrigation may perform some portion of the suite of ecological, biochemical, and hydrologic functions normally associated with natural riparian habitat. This heterogeneous landscape with a mosaic of habitat types may also be important to many wildlife species (Johnson et al., 1992). While we cannot say that these traditionally irrigated agriculture systems are critical to maintaining southwestern riparian function, we do propose that in the absence of natural riparian landscapes the hydrologic processes and resultant diverse vegetation communities represent an ecologically valuable mosaic that contributes to many functions that would be lost if the irrigation water were transferred out of floodplain agriculture irrigation systems.

Potential Effects of Land and Water Use Changes on Multiple Functions of Irrigated Floodplain Agriculture. The very real possibility of wide scale land- and water-use changes in the upper Rio Grande irrigated corridor raises the issue as to how a given set of changes might affect any hydrological and ecological functions currently operating. These changes could include ditch lining, different irrigation scheduling with reduced ditch flow, or complete conversion away from irrigated agricultural land use. Some key questions regarding the loss of irrigated agriculture functions include:

- To what extent does irrigation seepage provide temporary and efficient storage of water underground and affect hydrologic budgets. For example, could reduced seepage, reduced groundwater storage, and greater reliance on surface water storage in downstream reservoirs lead to increased evaporative losses?
- To what extent does groundwater return flow as augmented by seepage affect stream temperature and aquatic habitat?
- To what extent is increased shallow groundwater flow due to seepage benefiting shallow groundwater quality and protecting deeper groundwater quality, given increased human impacts on groundwater due to septic systems and other releases of water-borne contaminants to the environment?
- In what ways and to what extent does wildlife depend on seepage-supported habitat? For example, how would vegetation changes along the ditches affect use of the irrigated corridor as a travel corridor or nesting habitat?

Answers to these and other related questions are critical for proper planning, policies, and management of the upper Rio Grande watershed and will likely have implications for other watersheds in the southwestern United States and beyond.

In addition to impacts of land- and water-use changes on ecological functions, research is needed to determine impacts of these changes on social, cultural, and aesthetic functions provided by traditional irrigated agriculture. For example, in a rural sociology study Eastman et al. (1997) found that New Mexico *acequias* "are an indispensable element in traditional village culture." Various methods are available in the fields of agricultural economics and natural resource economics that could be used to conduct valuation studies on non-commodity outputs and non-market goods provided by traditional irrigated agriculture (Chee, 2004; Dobbs, 2004; Hall et al., 2004; Randall, 2002).

SUMMARY AND CONCLUSIONS

Secondary benefits of traditional irrigated agriculture systems in northern New Mexico were assessed from a multifunctional agriculture perspective. A field study examined hydrologic and associated riparian functions associated with traditional *acequia* conveyance ditches and flood irrigation. About 16% of the flow in an earthen *acequia* irrigation ditch seeped out of the ditch bed and banks. Combined ditch and field irrigation seepage raised shallow groundwater levels 1 to 1.2 m near the ditch and midway between the ditch and river. Direct observation indicates this seepage supports riparian vegetation habitat along the ditch and likely is important for river riparian vegetation and habitat.

Some aspects of traditional irrigated agriculture may resemble natural floodplain hydrologic processes, processes that are now restricted due to river alterations that include channelization and flood control structures. Flood irrigation is similar to and may provide functions performed by overbank flooding; also, irrigation ditches and laterals resemble and may provide functions of meandering channels and braided channels. Seepage and its contribution to groundwater return flow to the river may redistribute peak river flows to provide augmented river flows in late summer and fall.

Traditional irrigated agriculture systems of the arid/semiarid southwestern United States and northern Mexico have formed part of the agroecological landscape for hundreds of years. Although these systems are not purely natural, dramatically changing irrigation management could lead to less complex hydrologic functioning and a less ecologically healthy floodplain corridor. Given the current pressures to take land and water resources out of irrigated agriculture, it is imperative that more research be conducted to determine the multiple functions and services these agricultural systems may provide, and then to value those services in the context of the surrounding landscape. This research has revealed significant hydrologic functions that should be incorporated into conceptual frameworks for management of irrigation systems within the regional context of water- and land-use planning for maximum sustainable natural resource use.

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