Reviews in Fisheries Science, 14:79–89, 2006

ISSN: 1064-1262 print
DOI: 10.1080/10641260500341320

Surface Water–Groundwater Interactions Between Irrigation Ditches, Alluvial Aquifers, and Streams

ALEXANDER G. FERNALD[1] AND STEVEN J. GULDAN[2]

[1]Department of Animal and Range Sciences, New Mexico State University, Las Cruces, New Mexico, USA
[2]New Mexico State University Alcalde Agricultural Science Center, Alcalde, NM, USA

Improved descriptions of surface water–groundwater interactions are required for enhanced water resource management in irrigated areas of the western U.S. We are conducting a research project to determine surface water–groundwater interaction effects on hydrologic budgets and water quality along the upper Rio Grande in New Mexico. This article reports on the initial phase of the project to ascertain the effects of unlined irrigation ditch seepage on shallow groundwater at the Alcalde Science Center in north-central New Mexico. Results from two seepage tests in which 60- and 80 m-long impoundments were established in the Alcalde Ditch indicate that under normal ditch flow depths about 11 cm/day seeps out of the Alcalde Ditch. Based on flow estimates over the 9 km length of the Alcalde Ditch, at least 5% of the total ditch flow seeps out of the ditch bed and banks during the irrigation season. Water level measurements from monitoring wells showed that within 1 month of the beginning of ditch flow, irrigation seepage caused a raised water table and orientation of flow paths towards the river. Specific conductance measurements of surface and shallow groundwater indicated that surface water was the origin of shallow groundwater. Seepage from earthen ditches such as the one in this study could possibly have multiple benefits: diluting agricultural chemicals or septic tank leachate in shallow groundwater, providing groundwater recharge to shallow wells, and providing delayed return flow to the stream thus maintaining in-stream flow after peak runoff periods.

Keywords hydrologic budgets, hyporheic flow, irrigation ditch seepage, flow estimates, monitoring wells

Introduction

The body of knowledge on surface water–groundwater interactions has been built largely on studies of specific individual components of overall hydrologic systems. Until recently, surface water and groundwater have been treated separately in most research and management situations. It is now recognized that management of one affects the other

This material is based upon work supported in part by the New Mexico Agricultural Experiment Station and by the Cooperative State Research, Education and Extension Service, U.S. Department of Agriculture under Agreement No. 2005-34461-15661.

Address correspondence to Alexander G. Fernald, New Mexico State University, Department of Animal and Range Sciences, Box 30003, MSC3I, Las Cruces, NM 88003-8003. E-mail: fernald@nmsu.edu

(Winter et al., 1998; Hayashi and Rosenberry, 2002). Recent thought has recognized the important interactions between surface water and alluvial aquifers (Woessner, 2000).

Under losing river regimes, river seepage primarily flows out of the river channel into the alluvial aquifer. River seepage has been shown to cause temporary elevation of water tables in alluvial aquifers when river stage is elevated above the alluvial aquifer (Squillace, 1996). There can be significant interactions, such as hyporheic flow, between surface water and shallow groundwater. In hyporheic flow, surface water enters the stream bed and banks, follows shallow groundwater flow paths, and reemerges as surface water downstream (Harvey and Wagner, 2000). Research since the 1980's has revealed significant hyporheic flow along streams (Bencala and Walters, 1983; Dahm and Vallett, 1996). Most investigations of hyporheic exchange between surface water and groundwater have occurred on smaller streams (Morrice et al., 1997; Packman and Bencala, 2000). Recently it has been shown that even in large rivers, high percentages of total streamflow can enter and leave hyporheic flow paths (Fernald et al., 2001; Laenen and Bencala, 2001).

Ecological and water quality effects of hyporheic flow and surface water–groundwater exchange are significant, particularly in streams with porous substrates. Surface-subsurface exchange creates habitat for benthic macroinvertebrates (Grimm, 1996; Brunke and Gonser, 1997). Exchange across the streambed can result in microbially mediated chemical transformation of carbon, nitrogen, phosphorus, and other nutrients (Wondzell and Swanson, 1996; Mulholland et al., 1997). Exchange between surface water and groundwater can have important effects on water quality, both in the stream and in the alluvial aquifer. 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; Hinkle et al., 2001). This exchange acts as a natural water filtering process (Fernald et al., 2000).

In the face of increasing demands for scarce water resources throughout the western U.S., irrigators are confronting the option of lining earthen irrigation ditches with impervious materials to reduce ditch seepage and improve conveyance efficiency. Seepage from irrigation ditches has been reported to range from 1 to 80% of ditch flow (Bosman, 1993; Hotchkiss et al., 2001; Kahlown and Kemper, 2004). Lining ditches to reduce seepage may have the unintended consequence of limiting beneficial effects of ditch seepage. Along irrigated cropland corridors between irrigation ditches and rivers, potential hydrologic and water quality benefits of ditch seepage are derived from the close interaction between surface water and shallow groundwater. Irrigators and water management entities need to account for effects of this interaction, but lack information to guide decision-making. Insufficient data exist to fully characterize hydrologic and water quality functions of ditch seepage.

Studies of the hydrologic effects of seepage from irrigation ditches have shown that ditches are important sources of recharge to shallow groundwater. Research on infiltration basins showed groundwater recharge from irrigation seepage caused groundwater mounds beneath irrigation ditches that dissipated when ditch seepage stopped (Maurer, 2002). In systems where seepage from unlined ditches is 60 times greater than seepage from lined ditches, seepage from unlined ditches dramatically increased groundwater flows and caused elevated water tables (Drost et al., 1997). Lining irrigation ditches reduced the availability of shallow groundwater that supplied wells to irrigate cropland (Calleros, 1991). Stable isotope studies have confirmed the irrigation ditch seepage origin of recharge that causes a rise in local groundwater levels (Harvey and Sibray, 2001). Modeling studies have reinforced the temporal transience of this groundwater mound in shallow alluvial aquifers (Youngs, 1977; Ram et al., 1994; Yussuf et al., 1994). If lining ditches enables irrigators to consume more of the water entering a ditch, and there is less seepage and return flow, lining the ditches may affect timing and the amount of downstream river flow. Ditch seepage and the return flow it creates may attenuate and redistribute peak flows. In places where previously active meandering channels have been constrained by man-made structures, ditch seepage may replace hydrologic functions previously performed by floodplain relict channel features. Reduced return flow from lining ditches could potentially lead to reduced instream flow downstream of lined irrigation ditch systems.

The shallow groundwater flow caused by ditch seepage may have many benefits, including diluting contaminants such as agricultural chemicals or septic tank leachate in shallow groundwater, protecting deep groundwater quality by transporting contaminants away from the deeper aquifer, supplying groundwater recharge to shallow wells, and providing delayed return flow to the stream that becomes available to downstream users after peak runoff periods. In addition, water quality effects of ditch seepage have many physical parallels with stream-aquifer interaction effects. For example, stream temperatures can be cooled by the inputs of cool alluvial aquifer return flows provided by irrigation seepage (Stringham et al., 1998). Ditch seepage also supports ditch-side riparian vegetation with its many attendant wildlife, grazing, and aesthetic values.

Leaching from crop irrigation may also be an important source of groundwater recharge, but it has not been precisely distinguished from ditch seepage. At the field scale, applying the precise amount of irrigation needed to meet crop water requirements can minimize seepage below crops to groundwater. There may be undesirable consequences of this type of seepage due to transport of constituents like nitrate and salts beneath the root zone into the shallow groundwater.

In many locations such as north-central New Mexico, irrigation water is not metered so the amount of water applied during typical irrigation events is not clear. In New Mexico alone, there are at least 721 traditional "acequia" irrigation ditches along rivers and streams that support typically small-scale farming interspersed with developing small urban areas (Ackerly, 1996). Strong links between local communities and agriculture are formed by the reliance on community members for maintenance of acequias. Small-scale irrigators are facing pressures to transfer water rights out of agriculture into other uses. When these transfers occur, constraints are placed on the future successful agricultural production of farmers along each affected irrigation ditch. Ditch lining or rotational irrigation allocations that reduce ditch flow, reduce seepage from previously earthen ditches or reduce seepage during the irrigation season.

For alfalfa, one of the most widespread crops along the upper Rio Grande, water use is relatively well understood. Recent research indicates that alfalfa water-use efficiency is similar to other crops under favorable growing conditions (Asseng and Hsiao, 2000). Water losses below the rooting zone have been modeled for alfalfa stands, showing up to 50% leaching both at Kansas dryland sites and at New Mexico sites under carefully planned irrigation scheduling (Asare et al., 2000; Mankin and Koelliker, 2000). Combinations of field measurement and modeling work, with a basic suite of soil, vegetation, and climate data, have successfully estimated corn and soybean crop seepage losses (Ma et al., 1998; Cameira et al., 2000; Starks et al., 2003). Studies of fertilizer movement under corn have shown that tillage practices and drainage techniques affect the amount of nitrate that moves into shallow groundwater (Patni et al., 1998; Elmi et al., 2002). While these studies and modeling efforts have addressed leaching below the root zone and have shown water quality effects of leaching, they do not clearly illustrate the full range of hydrologic flow paths that carry crop irrigation water from the surface, through the root zone, and into shallow groundwater.

Transpiration from riparian vegetation is a significant source of groundwater withdrawal along rivers in semi-arid regions (Dahm et al., 2002). Along irrigation ditches, riparian evapotranspiration may intercept ditch seepage before it recharges shallow groundwater. Riparian evapotranspiration can draw down the alluvial aquifer water table and provide an important control on the hydraulic gradients that drive surface water–groundwater interactions (Winter et al., 1998). Streamside riparian evapotranspiration may intercept groundwater return flow, with the evapotranspiration causing fluctuations in river flow (Nyholm et al., 2003). If the water table is drawn down directly adjacent to the river, evapotranspiration may enhance or limit hyporheic flow, depending on substrate porosity, evapotranspiration rates, and local hydraulic gradients.

New Mexico Research

In 2002 we began a study of irrigation ditch seepage effects on surface water–groundwater interaction along the Rio Grande River corridor. Initial research has addressed the effects of ditch seepage on groundwater flow and water quality at New Mexico State University's Alcalde Sustainable Agriculture Science Center. From 2002 through 2004, ditch seepage rates were measured by establishing impoundments over a 60-m length of earthen ditch and an 80-m length of stone-bank ditch at the Alcalde Center. We measured seepage rates per cross-sectional channel width of 11.9 cm/day seepage from the stone-bank ditch and 10.7 cm/day seepage from the earthen ditch, yielding an average rate at the Alcalde Center of 11.3 cm/day. Stage was measured weekly at the Alcalde Center beginning in the 2003 irrigation season and a rating curve was constructed to calculate ditch flow from stage. Based on flow estimates over the 9.2-km length of the Alcalde Ditch, and assuming seepage per cross-sectional width of 11.3 cm/day from the entire Alcalde Ditch, at least 5% of the total ditch flow seeps out the ditch bed and banks during the irrigation season.

In 2002, three transects of 5-cm slotted PVC wells were installed to about 4 m below the winter water table (Figure 1). Water levels were measured weekly throughout the year beginning in 2003. We found that the shallow groundwater table responds to seepage from the irrigation ditch within 1 to 2 weeks of the onset of ditch flows. Irrigation seepage caused a raised water table and orientation of flow paths towards the river (Figure 2).

We measured specific conductance in milli-Siemens per centimeter (mS/cm) of ditch, well, and river water in the field with a water quality probe. Specific conductance is a measure of the electrical conductivity of water, and it increases with more dissolved solids in the water. In general, specific conductance signatures acted as a rudimentary tracer. Specific conductance of ditch water closely matched that of river water, and both were lower than groundwater (Table 1). Specific conductance in the wells increased when ditch flows were turned off, and then decreased with the resumption of ditch flow. These results corroborate the ditch seepage origin of shallow groundwater. These specific conductance data as well as preliminary major cation and anion analyses indicate ditch seepage reached shallow groundwater and moved with shallow groundwater flow across the irrigated corridor.

More than 2 years of weekly water level measurements reveal consistent seasonal patterns of shallow groundwater flow. Data from transect A presented in Figure 3 illustrate these patterns, which were similar to data from transects B and C (data not shown). Within 1 to 2 weeks of the onset of irrigation ditch flow, water levels began to rise near the ditch (in well A5) and in the middle of the irrigated corridor (in well A3). The water table at these locations continued to rise until mid-August, and then generally declined until the onset of the next year's irrigation season. Three to four concurrent spikes in water table elevation

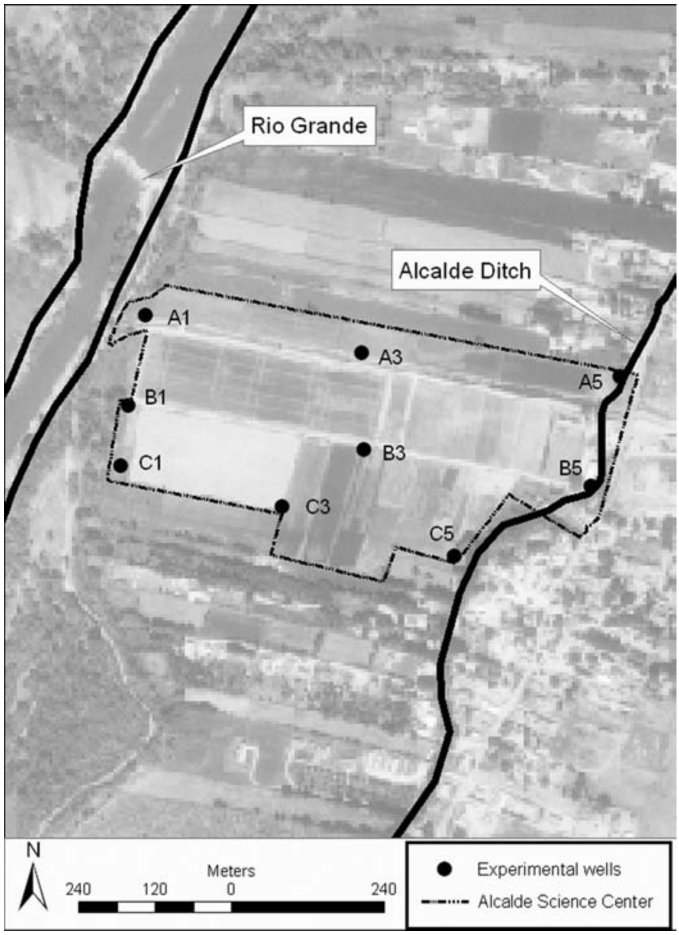

Figure 1. Alcalde Science Center experimental wells.

occurred in transect A wells, and these periods of rapid water table rise and fall were also seen in transect B and C wells. The water table farthest from the ditch and closest to the river (in well A1) exhibited fluctuations, of which some did and some did not correspond to the other two wells of transect A.

These seasonal patterns of shallow groundwater flow suggest important mechanisms in addition to ditch seepage that determine shallow groundwater flow dynamics. The rise in the water table after the onset of the irrigation season shows the movement of ditch seepage and possibly flood irrigation seepage into the irrigated corridor shallow groundwater. We have simulated alfalfa irrigation practices with parameterized hydrology and crop management components of the Root Zone Water Quality Model (Cameira et al., 2000). Initial simulation model runs indicate there is percolation below the rooting zone that would generate seepage to groundwater from flood irrigation. The spikes in water table elevation likely indicate seepage from lateral irrigation ditches and flood irrigation, consistent with rapid interaction between seepage and shallow groundwater. In wells near the river, the muted response of water levels shows possible effects of riparian evapotranspiration and river interaction with near-river shallow groundwater. A confluence of evapotranspiration, riparian groundwater

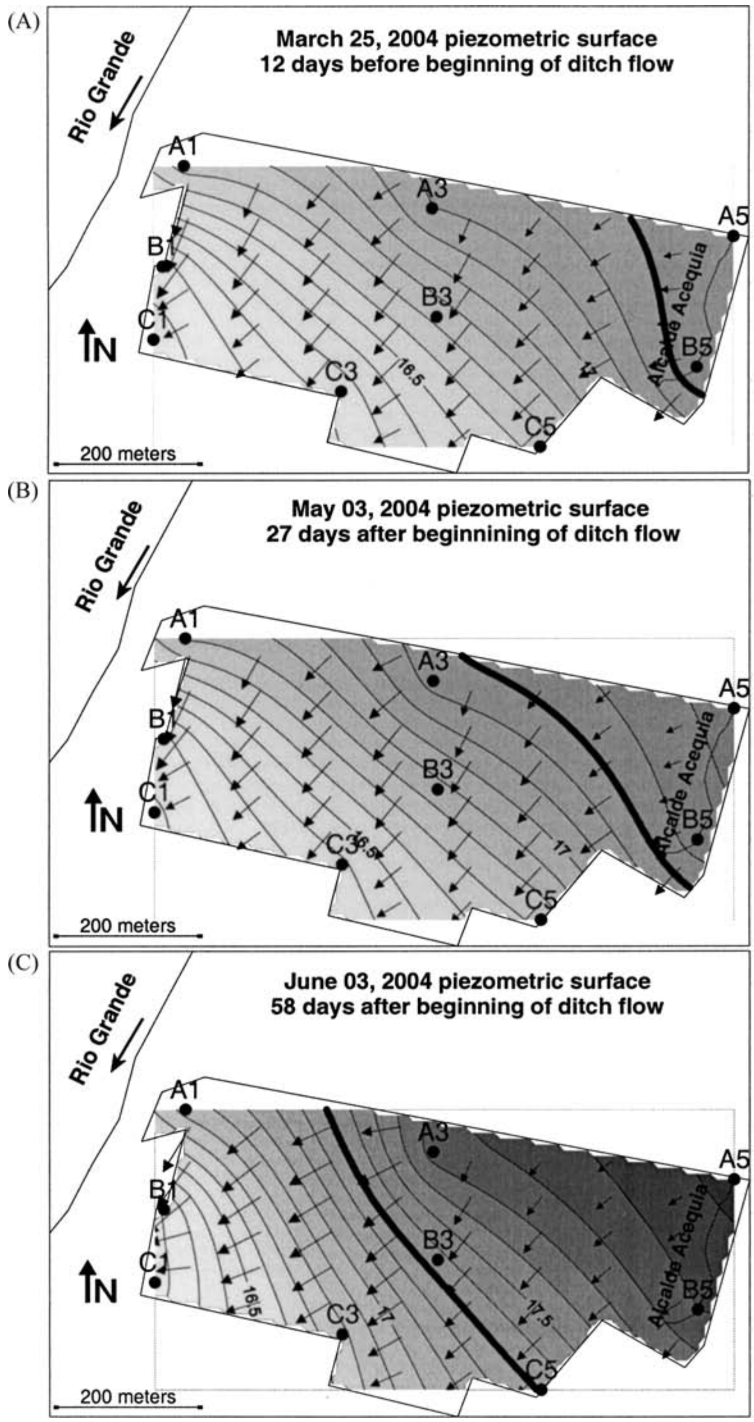

Figure 2. Water table elevations and shallow groundwater flow directions from water level measurements in three transects (A, B, C) of three wells each (1, 3, 5) at the Alcalde Science Center. (A) shows off-irrigation season conditions prior to the April 6 start of irrigation ditch flow. (B, C) show conditions 4 and 8 weeks (respectively) after irrigation ditch flows began. Irrigation ditch seepage created a rise in the shallow groundwater table, and groundwater flow paths oriented more towards the river.

Table 1
Specific conductance (mS/cm) along one transect of wells (A) between the Alcalde Ditch and the Rio Grande

Date	Ditch	A5	A3	A1	River
07/24/2003	0.327	0.452	0.765	0.735	0.348
08/28/2003	0.317	0.444	0.704	0.597	0.336
10/08/2003	0.321	0.452	0.707	0.629	0.329
12/10/2003	0.275	0.465	0.716	0.683	0.268
02/23/2004	No water	0.569	0.737	0.700	0.268
03/25/2004	No water	0.646	0.757	0.738	0.180
05/18/2004	0.183	0.475	0.731	0.717	0.188

levels, and river surface water levels likely combines to control the timing of water table declines in the late-irrigation and the post-irrigation season.

Questions for Future Research

Important scientific questions remain. At the fundamental process level these include the hydrologic effects of seepage from common flood irrigated crops and the interactions between the river seepage and the shallow groundwater. To better understand ditch seepage effects on shallow groundwater, it will be critical to have a better understanding of river

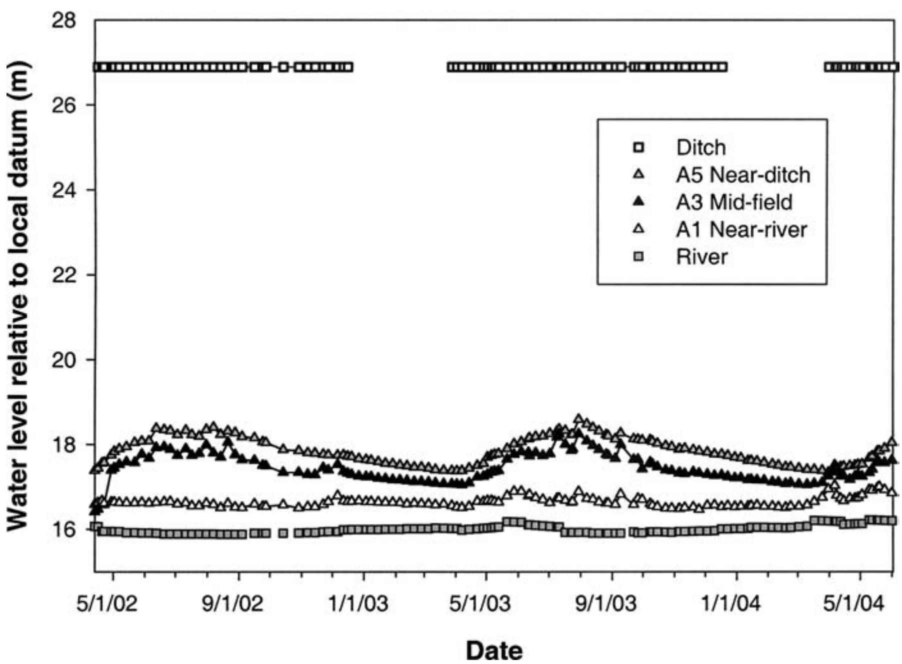

Figure 3. Response of shallow groundwater to seepage from irrigation ditch and flood irrigation at the Alcalde Science Center from 2002–2004 shown by: average water level in the Alcalde Ditch; water levels measured in three wells along a single transect (A); and estimated surface water level in the Rio Grande.

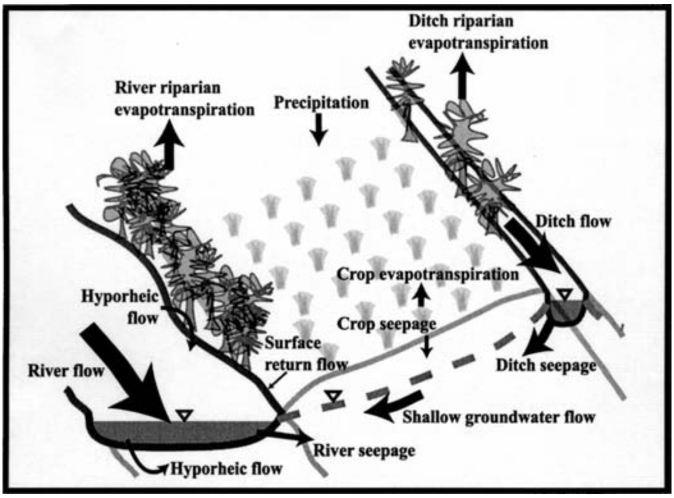

Figure 4. Components of hydrologic budget emphasizing surface water–groundwater interactions along irrigated corridor between unlined irrigation ditch and river; arrow widths are related to hypothesized magnitudes of irrigation season fluxes.

interactions with shallow groundwater. Research needs to be carried out to determine seasonal changes in river interaction with shallow groundwater. These interactions include river seepage that creates groundwater flows from the river into the irrigated corridor. Hyporheic flow may be most important when the river and shallow groundwater levels are similar and hydraulic gradients do not strongly move water only from (losing stream) or towards the river (gaining stream).

To fill gaps in scientific understanding, build on previous work, and provide relevant information for water resource management, specific research questions need to be addressed that apply to the physiographic setting of a cropland corridor between irrigation ditches and a river (Figure 4). These specific research questions include:

1. What are irrigation ditch seepage contributions to shallow groundwater flows beneath the cropland corridor?
2. What are seepage rates from the river to shallow alluvial groundwater and hyporheic flow rates into and out of the river channel bed and banks?
3. What are the major components of the total hydrologic budget of the irrigated corridor, and in particular, the magnitude of seepage from irrigation ditches compared to flood irrigation seepage from crops and evapotranspiration from riparian vegetation?
4. What are the effects of surface water–groundwater interaction on water quality of shallow groundwater and river water, specifically regarding temperature, total dissolved solids, and nitrate?
5. What seasonal patterns of ditch and river seepage correspond to maximum groundwater return flow and maximum hyporheic flow?
6. During which river flow and seasonal temperature regime does riparian vegetation evapotranspiration have the greatest effect on shallow groundwater flow?
7. Over long river reaches (10–200 km), what are the relative impacts of ditch seepage and hyporheic flow on river water quality?
8. What are the long-term hydrologic impacts of lining earthen irrigation ditches?

Initial research has characterized important interactions between ditch seepage and shallow groundwater flow. However, a thorough evaluation of the effects of ditch seepage in irrigated corridors requires comprehensive understanding of surface and subsurface hydrology, including flow in ditches and rivers, seepage from ditches and rivers, interaction of ditch and river surface water with shallow alluvial groundwater, hyporheic flow, seepage from crop irrigation, and evapotranspiration from crops and riparian vegetation. Investigation of these processes will provide irrigators, water resource managers, community members, and the scientific community with information to better manage natural resources through enhanced understanding of hydrologic and water quality functions of surface water–groundwater interactions in irrigated corridors.

References

Ackerly, N. W. A review of the historic significance and management recommendations for preserving New Mexico's Acequia systems. Prepared by Dos Rios Consultants Inc. for the Historic Preservation Division, Santa Fe, NM (1996).

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

Asseng, S., and T. C. Hsiao. Canopy CO_2 assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. *Field Crops Res.*, **67**: 91–206 (2000).

Bencala, K. E., and R. A. Walters. Simulation of solute transport in a mountain pool-and-riffle stream: A transient storage model. *Water Resour. Res.*, **19**: 718–724 (1983).

Bosman, H. H. A method for discriminating between evaporation and seepage losses from open water canals. *Water S.A.*, **19**: 171–175 (1993).

Brunke, M., and T. Gonser. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biol.*, **37**: 1–33 (1997).

Calleros, J. R. The impact on Mexico of the lining of the All-American Canal. *Natural Resour. J.*, **31**: 829–838 (1991).

Cameira, M. R., L. Ahuja, R. M. Fernando, and L. S. Pereira. Evaluating field measured soil hydraulic properties in water transport simulations using the RZWQM. *J. Hydrol.*, **236**: 78–90 (2000).

Dahm, C. N., J. R. Clevery, J. E. A. Coonrod, J. R. Thibault, D. E. McDonnell, and D. J. Gilroy. Evaporation at the land/water interface in a semi-arid drainage basin. *Freshwater Biol.*, **47**: 831–843 (2002).

Dahm, C. N., and H. M. Vallett. Hyporheic zones, pp. 107–110 **In**: *Methods in Stream Ecology* (Hauer, F. R., and G. A. Lambert, Eds.). San Diego, CA: Academic Press (1996).

Drost, B. W., S. E. Cox, and K. M. Schurr. Changes in ground-water levels and ground-water budgets, from predevelopment to 1986, in parts of the Pasco Basin, Washington. U.S. Department of the Interior/U.S.G.S. Water Resources Invest. Report No. 96–4086 (1997).

Elmi, A. A., C. Madramootoo, M. Egeh, A. G. Liu, and C. Hamel. Environmental and agronomic implications of water table and nitrogen fertilization management. *J. Environ. Qual.*, **31**: 1858–1867 (2002).

Fernald, A. G., P. J. Wigington, Jr., and D. H. Landers. Transient storage and hyporheic flow along the Willamette River, Oregon: Field measurements and model estimates. *Water Resour. Res.*, **37**: 1681–1694 (2001).

Fernald, A. G., D. H. Landers, and P. J. Wigington, Jr. Water quality effects of hyporheic processing, pp. 167–172. **In**: *Proceedings of the American Water Resources Association International Conference on Riparian Ecology and Management in Multi-Land Use Watersheds*, Portland, OR (2000).

Grimm, N. B. Surface-subsurface interactions in streams, pp. 625–646. **In**: *Methods in Stream Ecology* (Hauer, F. R., and G. A. Lambert, Eds.). San Diego, CA: Academic Press (1996).

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

Harvey, J. W., and B. J. Wagner. Quantifying hydrologic interactions between streams and their subsurface hyporheic zones, pp. 3–44. **In**: *Streams and Ground Waters.* (Jones, J. A., and P. J. Mulholland, Eds.). San Diego, CA: Academic Press (2000).

Hayashi, M., and D. O. Rosenberry. Effects of ground water exchange on the hydrology and ecology of surface water. *Ground Water*, **40**: 309–316 (2002).

Hinkle, S. R., J. H. Duff, F. J. Triska, A. Laenen, E. B. Gates, K. E. Bencala, D. A. Wentz, and S. R. Silva. Linking hyporheic flow and nitrogen cycling near the Willamette River - a large river in Oregon, USA. *J. Hydrol.*, **244**: 157–180 (2001).

Hotchkiss, R. H., P. E. Member, C. B. Wingert, and W. E. Kelly. Determining irrigation canal seepage with electrical resistivity. *J. Irrig. Drain. E-ASCE*, **127**: 20–26 (2001).

Kahlown, M. A., and W. D. Kemper. Seepage losses as affected by condition and composition of channel banks. *Agr. Water Manage.*, **65**: 145–153 (2004).

Laenen, A., and K. E. Bencala. Transient storage assessments of dye-tracer injections in rivers of the Willamette Basin, Oregon. *J. American Water Resour. Assoc.*, **37**: 367–377 (2001).

Ma, L., H. D. Scott, M. J. Shaffer, and L. R. Ahuja. RZWQM simulations of water and nitrate movement in a manured tall fescue field. *Soil Sci.*, **163**: 259–270 (1998).

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

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

Morrice, J. A., H. M. Vallett, C. N. Dahm, and M. E. Campana. Alluvial characteristics, groundwater-surface water exchange and hydrological retention in headwater streams. *Hydrol. Process.*, **11**: 253–267 (1997).

Mulholland, P. J., E. R. Marzolf, J. R. Webster, D. R. Hart, and S. P. Hendricks. Evidence that hyporheic zones increase heterotrophic metabolism and phosphorus uptake in forest streams. *Limnol. Oceanogr.*, **42**: 443–451 (1997).

Nyholm, T., K. R. Rasmussen, and S. Christensen. Estimation of stream flow depletion and uncertainty from discharge measurements in a small alluvial stream. *J. Hydrol.*, **274**: 129–144 (2003).

Packman, A. I., and K. E. Bencala. Modeling surface-subsurface hydrological interactions, pp. 45–80. **In:** *Streams and Ground Waters.* (Jones, J. A., and P. J. Mulholland, Eds.). San Diego, CA: Academic Press (2000).

Patni, N. K., L. Masse, and P. Y. Jui. Groundwater quality under conventional and no tillage: I. Nitrate, electrical conductivity, and pH. *J. Environ. Qual.*, **27**: 869–877 (1998).

Pinay, G., and H. Decamps. The role of riparian woods in regulating nitrogen fluxes between the alluvial aquifer and surface water: A conceptual model. *Regul. River Res. Manage.*, **2**: 507–516 (1988).

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

Sjodin, A. L., W. M. Lewis, and J. F. Saunders III. Denitrification as a component of the nitrogen budget for a large plains river. *Biogeochemistry*, **39**: 327–342 (1997).

Squillace, P. J. Observed and simulated movement of bank-storage water. *Ground Water*, **34**: 121–134 (1996).

Starks, P. J., G. C. Heathman, L. R. Ahuja, and L. W. Ma. Use of limited soil property data and modeling to estimate root zone soil water content. *J. Hydrol.*, **272**: 131–147 (2003).

Stringham, T. K., J. C. Buckhouse, and W. C. Krueger. Stream temperatures as related to subsurface waterflows originating from irrigation. *J. Range Manage.*, **51**: 88–90 (1998).

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

Yussuf, S. M., H. S. Chauhan, M. Kumar, and V. K. Srivastava. Transient canal seepage to sloping aquifer. *J. Irrig. Drain. E-ASCE.*, **120**: 97–109 (1994).

Winter, T. C., J. W. Harvey, O. L. Franke, and W. M. Alley. Ground water and surface water, a single resource. U.S.G.S. Circular No. 1139(79). Denver, CO (1998).

Woessner, W. W. Stream and fluvial plain ground water interactions: Rescaling hydrogeologic thought. *Ground Water*, **38**: 423–434 (2000).

Wondzell, S. M., and F. J. Swanson. Seasonal and storm dynamics of the hyporheic zone of a 4th-order mountain stream. II: Nitrogen cycling. *J. N. Am. Benthol. Soc.*, **15**: 20–34 (1996).