Shallow Aquifer Recharge from Irrigation in a Semiarid Agricultural Valley in New Mexico

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Abstract: Irrigation percolation can be an important source of shallow aquifer replenishment in arid regions of the southwestern United States. Aquifer recharge derived from irrigation percolation can be more significant in fluvial valleys overlying shallow aquifers, where highly permeable soils allow rapid water infiltration and aquifer replenishment. This study used data from various irrigation experiments and data at the piezometric level to assess the irrigation percolation effects on the recharge of a shallow aquifer in an agricultural valley of northern New Mexico. The water balance method (WBM) and the water table fluctuation method (WTFM) were used to estimate aquifer recharge at the field scale (<1 ha) and the WTFM was used to determine recharge at the entire valley scale (40 km^2). Also, the temporal and spatial distribution of aquifer response to irrigation percolation and canal seepage inputs was characterized. The results showed that for separate irrigation events at the field scale, aquifer recharge values ranged from 0 to 369 mm when using the WBM and from 0 to 230 mm when using the WTFM. For the cumulative irrigation season at the valley scale, recharge ranged from 1,044 to 1,350 mm $year^{-1}$. A relatively rapid water table response with sharp water table rises and declines was observed in all but dryland location wells in response to canal seepage and irrigation percolation inputs. The results of this study add to the understanding of the mechanisms of shallow aquifer recharge and the interactions between surface water and groundwater in a floodplain agricultural valley of northern New Mexico. **DOI: 10.1061/(ASCE)HE.1943-5584.0000718.**

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Introduction

Shallow aquifers can be important sources of groundwater supply in arid and semiarid regions such as the southwestern United States. Deep percolation from irrigation may account for a significant volume of the replenishment of these shallow aquifers (Schmidt and Sherman 1987; Singh et al. 2006; Willis and Black 1996). Proper quantification of aquifer recharge and a good understanding of the interactions between surface water and groundwater is greatly important in these water-limited regions. A proper quantification of groundwater recharge is important to better understand the capacity of the aquifer for providing groundwater supply. However, calculating aquifer recharge is one of the most difficult tasks when assessing groundwater resources (Sophocleous 1991).

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Different methods commonly used for quantifying the rate of aquifer recharge can be subdivided into categories of surface water and vadose zone, and groundwater. In the surface water and vadose zone category, methods like heat tracers, seepage meters, zero flux plane, lysimeters, environmental tracers (i.e., chloride), and the water balance method are commonly used (Healy and Cook 2002). The water balance method (WBM) can be used to estimate potential aquifer recharge coming from irrigation-deep percolation. The WBM has been successfully used for determining deep percolation below the root zone (Jaber et al. 2006; Ochoa et al. 2007; Sammis et al. 1982), and in many vadose zone studies, deep percolation is often equated to aquifer recharge (Scanlon et al. 2002). The use of the WBM for estimating aquifer recharge is based on the premise that water that percolates below the root zone has the potential to reach the water table. When reliable field observations are available, the WBM can provide good estimates of potential aquifer recharge. In the WBM, potential aquifer recharge is the unknown variable and the rest of the water balance parameters (irrigation and rainfall, evapotranspiration, runoff, and change in soil water storage) are measured or estimated (Ben-Asher and Ayars 1990).

In the groundwater category, methods such as the water table fluctuation method, environmental tracers, and historical tracers are commonly used (Healy and Cook 2002). The water table fluctuation method (WTFM) provides a simple approach to quantify the rate of aquifer recharge. The abundance of groundwater level data and the simplicity of the method for estimating recharge from transient water table fluctuations or groundwater-level spatial patterns makes the WTFM one of the most widely used methods for estimating aquifer recharge (Healy and Cook 2002). The WTFM implies that transient water table rises are directly related to recharge water arriving to the water table (Nimmer et al. 2010;

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Scanlon et al. 2002). The WTFM combines the specific yield of the unconfined aquifer and the fluctuations in the water table for calculating changes in groundwater storage (Sophocleous 1991).

Different methods in the surface water and vadose zone category mostly rely on indirect observations of infiltration. However, methods in the groundwater approach tend to ignore soil infiltration processes and can result in errors in estimating aquifer recharge (Sumner et al. 1999). Uncertainties in the calculation of aquifer recharge by different methods highlights the importance of using multiple techniques to increase the reliability of recharge estimates (Healy and Cook 2002; Nimmo et al. 2003; Scanlon et al. 2002). It is recommended that aquifer recharge be estimated by using different methods, so the results can be compared (Healy and Cook 2002; Nimmo et al. 2003).

Aquifer recharge derived from irrigation percolation can be more significant in fluvial valleys overlying shallow aquifers, where highly permeable soils allow rapid water infiltration and aquifer replenishment. This is common in the fluvial agricultural valleys of northern New Mexico, where highly permeable soils and flood irrigation combine to cause a rapid recharge of the shallow aquifer (Fernald et al. 2010; Ochoa et al. 2009). Objectives of this study conducted in an agricultural valley of northern New Mexico were: (1) at the field scale, determine and compare shallow aquifer recharge by the WBM and WTFM; and (2) at the valley scale, determine shallow aquifer recharge and characterize temporal and spatial variability of water table fluctuations in response to direct and localized aquifer recharge.

Materials and Methods

Study Area

The study area encompasses a portion of the Española valley of approximately 20 km long by 2 km wide along the Rio Grande in northern New Mexico (Fig. 1). For the purposes of this research, the study area is described as the Alcalde-Velarde valley. In northern New Mexico, relatively small agricultural valleys are commonly spread on the alluvial deposits along the Rio Grande. Most of these agricultural valleys use traditional irrigation systems where water is gravity driven into irrigation canals that run along the valley, and in most cases, connect with the river at some point

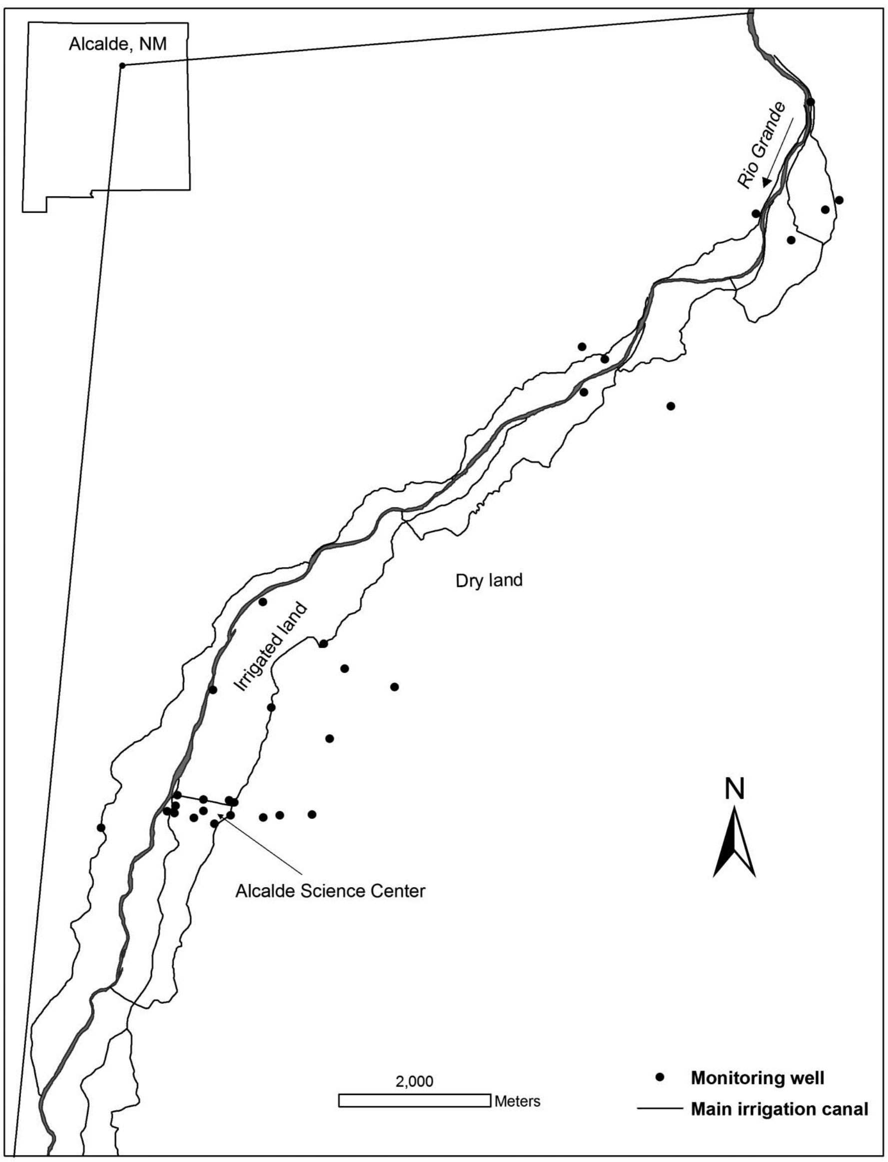

Fig. 1. Map of the study area showing the network of main irrigation canals and monitoring wells used in this study

downstream. Water from main canals is either diverted into smaller irrigation canals or applied directly to crop fields adjacent to the canals. This is the case of the Alcalde-Velarde valley, where the irrigated cropland portion of the valley comprises an agriculture corridor that is delimited by the Rio Grande and a series of different irrigation canals on the east and west sides of the river. These irrigation canals are primarily earthen structures with relatively short sections of rock and/or cement lining. These canals irrigate various forage, fruit, and vegetable crops, primarily using surface (border and furrow) irrigation water that is gravity driven from the Rio Grande. Most of the water in the Alcalde-Velarde valley is used for agriculture purposes (Ortiz et al. 2007), with approximately 99% coming from surface water sources (Cevik 2009).

The study area overlies a shallow unconfined aquifer with depth to water table generally ranging from 1.5 to 10 m in the irrigated portion of the valley and from 10 to 30 m in the dryland portion, depending on the proximity to the river, which is measured at the lowest level before the onset of the irrigation season. Regional groundwater flow is mostly influenced by the Rio Grande and by drainage from tributaries coming from the Sangre de Cristo Range in the east side of the basin (Stephens 2003). In the Alcalde-Velarde valley, the Rio Grande is considered to be a gaining stream (Helmus et al. 2009) and the slope of the water table is approximately 0.2% (Ochoa et al. 2009).

Average annual precipitation in the study area is 251 mm, of which 40% occurs during the summer season. For the period of record, 1953 to 2006, the average monthly temperature was 10.6°C, with the lowest average monthly temperature of −0.81°C during the month of January and the highest average monthly temperature of 22.37°C during the month of July [Western Regional Climate Center (WRCC) 2006]. Elevation above mean sea level in the research area ranged from 1,725 m, by the Rio Grande, to 1,756 m, in the dryland portion of the valley.

It is common that irrigation systems are established in areas of low precipitation and low natural recharge; therefore, groundwater recharge from irrigation is relatively larger than groundwater recharge from precipitation (Winter et al. 1998). According to Cevik (2009), areal recharge in the entire Española basin, including precipitation and streambed recharge, does not exceed 5% of the annual precipitation. Also, the horizontal hydraulic conductivity of the valley alluvium ranges between 0.3 and 1 $\mathrm{m\,day^{-1}}$ (Hawley and Kernodle 2000).

Water that reaches the water table can come laterally or from above (Fetter 1994). This study focused on aquifer recharge coming from above, primarily from irrigation percolation and from canal seepage. This is based on the relatively low influence of areal recharge from precipitation and streambed and the low horizontal conductivity in the area, which suggests that some other sources like irrigation may have a stronger influence on aquifer recharge in the Alcalde-Velarde valley. The WBM and WTFM were used to determine shallow aquifer recharge at the field scale (≤1 ha) and the WTFM was used at the valley scale (~40 $\mathrm{km^2}$). Also, piezometric level data were used to characterize the temporal and spatial distribution of water table fluctuations throughout the valley.

Water Balance Method: Field Scale

Data from several irrigation experiments, conducted from 2005 through 2009 at the Alcalde Science Center, were used to estimate potential aquifer recharge from irrigation percolation. These irrigation experiments were conducted in alfalfa-grass, oat-wheatgrass, and apple crops, which represent common crops in the valley. The WBM was used to calculate shallow aquifer recharge (Re) after different irrigation events in these crop fields.

$$\mathrm{Re} = \mathrm{IRR} + P - \Delta S - \mathrm{RO} - \mathrm{ET} \tag{1}$$

where Re = potential recharge from deep percolation (mm); IRR = irrigation depth (mm); P = rainfall (mm); ΔS = change in soil water storage (mm); RO = field runoff (mm); and ET = evapotranspiration (mm).

Re was determined as the deep percolation water passing below the upper first meter of soil depth after each irrigation event. Irrigation depth was calculated based on the total volume of water applied to each crop field (measured on site with a propeller flow meter) divided by each field area. Rainfall data were obtained from a National Oceanic and Atmospheric Administration (NOAA) weather station located at the Alcalde Science Center. Measurements of soil water content were used to determine the change in soil water storage in the top 1-m soil profile of each of the four evaluated crop fields. The ΔS was determined by subtracting soil water content (θ) measured at the onset of irrigation from soil water content measured 24 h after the end of each irrigation event. Measurements of θ were obtained at different soil depths in the top 1 m of soil by using time domain reflectometry based sensors (Campbell Scientific, Logan, Utah) that were calibrated for each specific depth and soil type in the different crop fields (Ochoa et al. 2007, 2009, 2011). Field runoff was measured by using Samani-Magallanez flumes (Samani and Magallanez 2000) that were installed at the end of the oat-wheatgrass fields. The results from these flumes were compared to manual measurements of runoff flow obtained with an acoustic Doppler velocimeter (YSI, San Diego, California) after one irrigation event in each of the oat grass fields. No significant differences in runoff estimates were observed between these two devices. The alfalfa-grass and apple fields had berms surrounding the fields that prevented any irrigation runoff from occurring on these fields. Actual evapotranspiration was obtained from the website of the New Mexico Climate Center (NMCC 2010), which uses data collected from a weather station located at the Alcalde Science Center. Actual evapotranspiration was calculated by using reference crop evapotranspiration equations by Hargreaves and Samani (1985) and crop coefficients reported by Samani and Pessarakli (1986). The weather station at the Alcalde Science Center is located relatively close to the crop fields, with 260 m to the center of the nearest field (alfalfa-grass) and 500 m to the center of the farthest field (oat-wheatgrass with clay loam soil). In the case of fields where a crop mix was present (alfalfa-grass and oat-wheatgrass), the dominant crops of alfalfa and oats were considered for calculating evapotranspiration. Growing periods for the crops evaluated were considered as follows: alfalfa, early April to late October; oats, early June to late August; and apples, mid-April to mid-October.

Soil type and depth to water table play an important role in the mechanisms of water transport through the vadose zone and in regulating timing and amount of percolation water that arrives to the water table (Ochoa et al. 2009). Soil type and depth to base flow water table were different in the crop fields evaluated in this study. Soils of the alfalfa-grass field and of one oat-wheatgrass field are classified as Fruitland sandy loam (SL), soil of one oat-wheatgrass field is classified as a Werlog clay loam (CL), and soils of the apple orchard are classified as Alcalde clay and SL (Soil Survey Staff 2011). Depth to water table ranged from 2.5 m in one oat-wheatgrass field (CL), to 4 m in the apple orchard and one oat-wheatgrass field (SL), to 5 m in the alfalfa-grass field. The four different experimental crop fields covered an area of less than one hectare each. The smallest field was the apple orchard (0.5 ha), followed by the alfalfa-grass field (0.7 ha) and by the two oat grass fields (1 ha each).

One of the limitations of the water budget approach is that potential recharge is the sink term; because of this, it heavily

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depends on the accurate measurement or calculation of the remaining parameters (Scanlon et al. 2002; Sophocleous 1991). Among the potential sources of error associated with the use of this method are those that relate to the physical measurement of the different water budget components and those that relate to the spatial domain of these variables. Accurate rates of aquifer recharge are always desired; however, it goes beyond the current capabilities of this study to determine the uncertainty associated with any aquifer recharge estimate (Healy 2010). Data collection errors were minimized by calibrating the different instrumentation (i.e., soil moisture sensors) to specific field conditions. However, beyond instrumentation calibration, there are some errors associated with irrigation water application and redistribution through the vadose zone that are beyond the authors' control. Some assumptions inherent to water application and redistribution were made. For instance, it was assumed that soil moisture data collected at certain point locations and at different soil depths were representative of the entire field. Also, it was assumed that all irrigation water percolating the top 1 m soil reached the shallow aquifer in less than 24 h after the end of each irrigation event. In addition, it was assumed that there were no significant water losses to lateral flow. This was based on the relatively rapid groundwater level rise observed in response to deep percolation during different irrigation events.

Fig. 2 illustrates the approach used for calculating potential aquifer recharge in the apple orchard and that was similar for the other three experimental fields. Soil water content sensors were installed at different soil depths to determine the change in water storage in the top 1 m soil profile. Data collected were integrated to calculate the amount of irrigation water percolating below the top 1 m, which was equated to potential aquifer recharge. Although in some crops, such as alfalfa, roots can extend below 2 m, most of the root mass and water uptake is in the top 1 m (Abdul-Jabbar et al. 1982; Kohl and Kolar 1976; Ochoa et al. 2011). Therefore, it was assumed that root uptake from water percolating below the top 1 m soil profile was minimal and that all of the percolation water would reach the shallow aquifer.

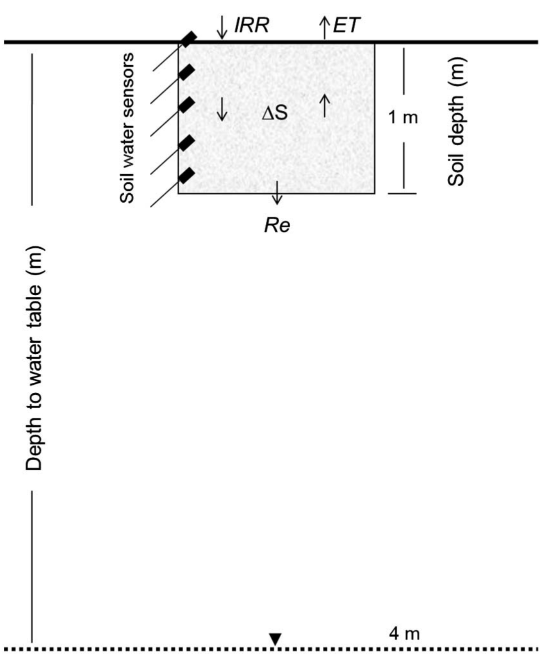

Fig. 2. Schematic showing installation of soil water content sensors and the different water budget components used to estimate potential aquifer recharge in the apple orchard

Water Table Fluctuation Method: Field Scale

The WTFM was used to calculate shallow aquifer recharge by using the following equation after Risser et al. (2005):

$$\mathrm{Re} = \Delta h \times Sy \tag{2}$$

where Re = aquifer recharge (mm); Δh = change in water level (mm); and Sy = specific yield or fillable porosity of the unconfined aquifer. To quantify the change in water level, piezometric level data were used from monitoring wells installed in the experimental fields at the Alcalde Science Center. Four wells were located in the alfalfa-grass field (Ochoa et al. 2007), nine wells were located in the two oat-wheatgrass fields (Ochoa et al. 2011), and two more wells were located in the apple orchard (Fig. 3).

The WTFM works best in areas with shallow water tables, where sharp transient water table rises and declines are observed over short periods of time (Healy and Cook 2002). This is the case in the experimental crop fields located at the Alcalde Science Center, where depth to water table, measured at the lowest level prior to the onset of the irrigation season, ranges from 2.5 m in one of the oat-wheatgrass fields to 5 m in the alfalfa-grass field. Also, sharp water table rises and declines have been observed during the few hours following the onset of irrigation (Ochoa et al. 2007). One of the difficulties in applying the WTFM is determining a representative value for Sy (Scanlon et al. 2002). Sy indicates the volume of water drained out of the unconfined aquifer when the water table drops. Sy is defined as the ratio of the volume of water that drains freely from saturated earth material due to gravity forces to the total volume of the earth material (Brooks et al. 2003). Sy is normally expressed as a ratio between 0 and 1; it is less than the porosity because some water can be trapped in the pore space.

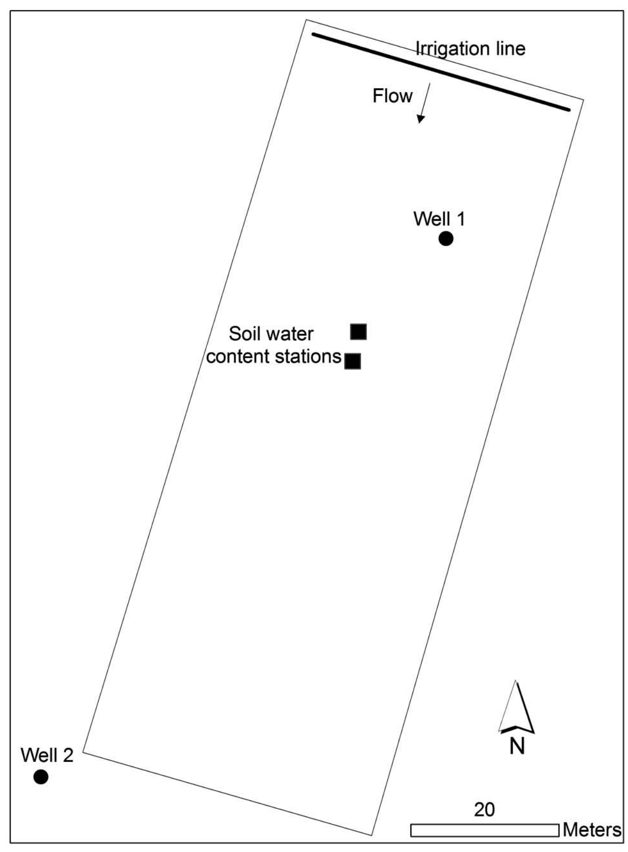

Fig. 3. Schematic showing instrumentation and well locations in the apple orchard

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In the Tesuque system, where the Alcalde-Velarde valley is located, no aquifer tests have been conducted long enough to determine *Sy* (Cevik 2009). Therefore, literature values were used for *Sy* that are based on values of porosity for unconsolidated materials. Porosity values were estimated based on the medium to coarse sand and medium gravel layer observed in the water table fluctuation zone of six pits excavated during a previous water transport experiment at the Alcalde Science Center (Ochoa et al. 2009). An average specific yield of 0.28 was obtained based on *Sy* values for unconsolidated alluvial deposits (medium to coarse sand and medium gravel) reported by Dingman (2002).

Water Table Fluctuation Method: Valley Scale

The WTFM was used for calculating aquifer recharge by using piezometric level data collected from multiple wells in the Alcalde-Velarde valley. Water level measurements obtained from a monitoring well represent an area of at least several tens of square meters; therefore, the WTFM can be used as an integrated approach that goes beyond only single point measurements of the water table (Healy and Cook 2002). A total of 31 wells were used for monitoring water level fluctuations in the Alcalde-Velarde valley. Fifteen nonpumping monitoring wells (50 mm diameter) were installed in the irrigated portion of the valley and 16 wells were used from collaborators in the dry land portion. Collaborator wells showed variable levels of use, ranging from marginal, to household use, to heavy use (in one case). All wells were equipped with standalone water level loggers (model U20-001-01, Onset Computer, Bourne, Massachusetts) programmed for hourly data collection. Also, a water level indicator (Model 16036, Durham Geo Slope Indicator, Mukilteo, Washington) was used to measure water levels during selected dates. These water level data were used for verification or calibration of the water level data obtained with the automated water level loggers. All wells were geopositioned with a GPS unit (Model Pro XRS, Trimble Navigation, Sunnyvale, California) and were surveyed for elevation with a total station (Model GTS 226, Topcon Positioning Systems, Pleasanton, California).

Water table fluctuations occur in response to spatial recharge; the time of response ranges from event scale to long-term scale (Scanlon et al. 2002). Daily averaged groundwater level data collected from 20 monitoring wells were integrated to estimate seasonal aquifer recharge at the valley scale for 2007 through 2009. Only data from nonpumping or minimal use wells were used to estimate recharge. Porosity values similar to those observed at the Alcalde Science Center, and consequently similar *Sy*, were assumed for the entire Alcalde-Velarde valley.

Spatial and Temporal Variability of the Water Table

The effects of direct (from irrigation percolation) and localized (from main canal seepage) aquifer recharge in the Alcalde-Velarde valley were characterized. Piezometric level data, collected to characterize the temporal variability of the water table, were integrated and averaged. To characterize the spatial effect, piezometric level data were used from individual wells placed at variable distance from the primary irrigation canal. For this purpose, three transects (1, 2, and 3) were established with wells located at near river, near canal, and dry land locations (Fig. 4). In addition, a midirrigation field was also monitored in Well Transect 1.

Also, the time and magnitude of water table fluctuations in response to canal seepage were evaluated along one of the primary irrigation canals (Fig. 4). Data collected from a stilling well located in the Alcalde main canal (at the Alcalde Science Center) were used to characterize the surface water time of arrival at the beginning of the canal flow season (April–November). Data collected from a monitoring well in Transect 1, which is located 3 m from the main canal and 20 m upstream from the stilling well, were used to characterize the canal seepage water time of arrival to the aquifer. Both the stilling well and the monitoring well were equipped with water level loggers and electrical conductivity (EC) meters (model CS547A, Campbell Scientific). After water reached the stilling well at the onset of each irrigation season, the first indication of water table rise in the monitoring well was examined to determine the time of arrival of canal seepage water to the water table. Collected EC data were used as a tracer to validate the canal origin of water that reached the water table. A decrease in EC in the monitoring well also indicated the arrival of canal seepage water.

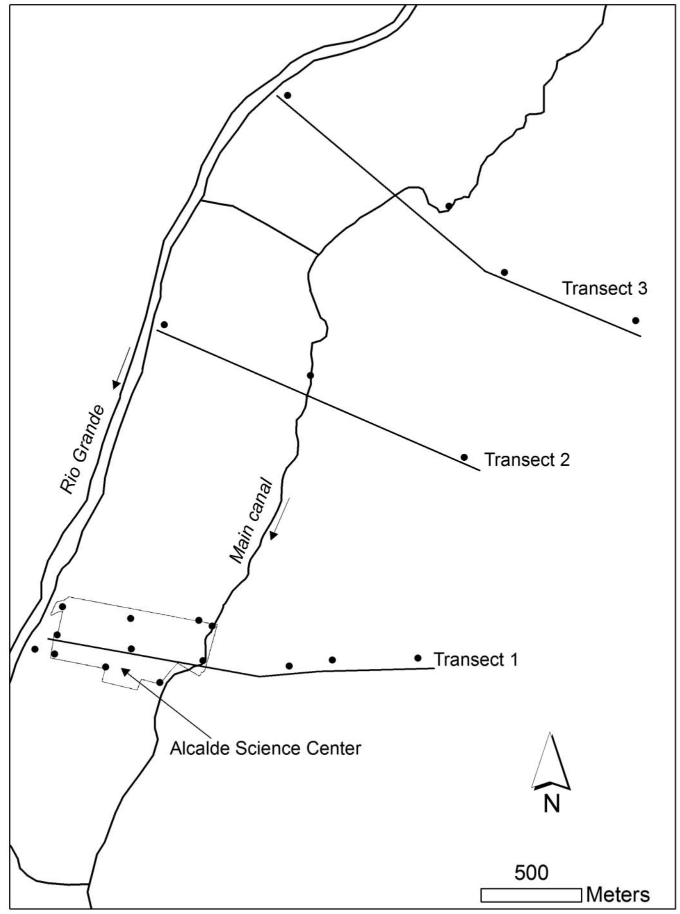

Fig. 4. Well transects in the Alcalde-Velarde valley

Results and Discussion

Water Balance Method: Field Scale

A daily WBM was used to calculate potential aquifer recharge from irrigation percolation in four different crop fields with different soil types and variable depths to the water table. Table 1 shows the results for the different components (IRR, P, ΔS, RO, and ET) of the water balance and the residual, which is the potential Re for different irrigation dates in different crop fields. Irrigation applications ranged from 41 mm in the oat-wheatgrass field with sandy loam soil to 462 mm in the apple orchard. Marginal levels (2 and 4 mm) of precipitation were observed during two irrigation dates (October 20, 2008 and June 4, 2009) in the oat-wheatgrass field with SL soil.

Table 1. Re Calculated by the Daily WBM for Different Crops with Different Soil Types

Date	IRR	P	ΔS	RO	ET	Re
	(mm)					
Alfalfa-grass (SL soil)						
May 19, 2005	216	0	156	0	8	52
June 15, 2005	246	0	138	0	9	99
July 6, 2005	219	0	87	0	8	124
July 27, 2005	298	0	112	0	4	182
September 1, 2005	175	0	91	0	8	76
April 24, 2006	317	0	159	0	8	150
June 7, 2006	390	0	146	0	8	236
August 2, 2006	154	0	85	0	4	65
September 21, 2006	125	0	93	0	7	25
Apple orchard (CL and SL soil)						
May 24, 2006	385	0	35	0	6	344
June 22, 2006	462	0	84	0	9	369
June 20, 2007	213	0	161	0	8	44
July 17, 2007	204	0	128	0	9	67
October 26, 2007	284	0	329	0	5	0
Oat-wheatgrass (CL soil)						
June 10, 2008	211	0	31	14	9	157
June 24, 2008	187	0	34	17	7	129
July 7, 2008	85	0	24	9	4	48
August 12, 2008	59	0	44	0	4	10
September 9, 2008	81	0	94	11	5	0
October 28, 2008	42	0	50	0	4	0
April 29, 2009	122	0	34	2	8	79
May 21, 2009	97	0	63	5	4	26
June 15, 2009	93	0	62	7	8	17
July 13, 2009	88	0	111	1	1	0
July 27, 2009	85	0	109	16	9	0
September 2, 2009	103	0	140	6	4	0
Oat-wheatgrass (SL soil)						
June 16, 2008	267	0	104	42	9	113
July 1, 2008	96	0	60	22	5	8
July 14, 2008	125	0	41	40	4	40
August 7, 2008	87	0	95	39	4	0
September 11, 2008	74	0	52	16	4	2
October 20, 2008	41	2	84	0	3	0
May 6, 2009	84	0	69	8	9	0
June 4, 2009	117	4	173	24	8	0
June 25, 2009	85	0	86	8	7	0
July 20, 2009	85	0	73	2	8	2
August 10, 2009	85	0	67	9	9	0
September 1, 2009	101	0	149	35	4	0
Mean (standard deviation)	162.8 (51)	0.2 (1)	96.1 (39)	8.8 (13)	6.4 (2)	64.8 (46)

The average change in ΔS was 96.1 mm, with values ranging from 24 mm in the oat-wheatgrass field with CL soil to 329 mm in the apple orchard. Average RO was 8.8 mm and was only observed in the two oat-wheatgrass fields. Crop ET ranged from 1 to 9 mm, with an average across crops of 6.4 mm. In general, higher irrigation applications resulted in higher potential aquifer recharge, regardless of crop or soil type. The highest Re value (369 mm) was observed following a 462-mm irrigation application in the apple orchard on June 22, 2006.

Water Table Fluctuation Method: Field Scale

The WTFM was used to calculate Re following irrigation in four different crop fields. Aquifer recharge was obtained based on water table fluctuations recorded hourly in wells located at variable distances from the irrigation line (Tables 2 and 3). For instance, the levels of aquifer recharge in the alfalfa-grass field were calculated based on wells located 2, 3, and 85 m from the water line and the wells in the apple orchard were located 20 and 110 m away from the water line (Fig. 3). Wells located in the two oat-wheatgrass fields were located 20, 50, and 120 m away from the water line.

Table 2. Re Calculated by the WTFM for an Alfalfa-Grass Field and an Apple Orchard

		Well distance from irrigation line (m)				
		2	3	20	85	110
	IRR rate	Re				
Date	(mm h^{-1})	(mm)				
Alfalfa-grass with SL soil						
May 19, 2005	31	29	NA	—	NA	—
June 15, 2005	31	97	59	—	25	—
July 6, 2005	32	99	80	—	NA	—
July 27, 2005	34	105	83	—	57	—
September 1, 2005	24	61	44	—	34	—
April 24, 2006	29	40	126	—	21	—
June 7, 2006	33	85	93	—	59	—
August 2, 2006	26	13	9	—	19	—
September 21, 2006	19	2	1	—	4	—
Apple orchard with CL and SL soil						
May 24, 2006	55	—	—	230	—	81
June 22, 2006	58	—	—	185	—	69
June 20, 2007	31	—	—	73	—	5
July 17, 2007	23	—	—	213	—	8
October 26, 2007	39	—	—	123	—	0

Note: NA indicates not available.

Table 3. Re Calculated by the WTFM for Two Oat-Wheatgrass Fields with Different Soil Types

		Well distance from irrigation line (m)				
		20	50	50	50	120
	IRR rate	Re				
Date	(mm h^{-1})	(mm)				
Oat-wheatgrass with CL soil						
June 10, 2008	8	1	4	0	0	0.3
June 24, 2008	8	68	49	38	68	31
July 7, 2008	7	3	0	4	0	0.3
August 12, 2008	8	0	0	0	0	0
September 9, 2008	11	0	0	0	0	0
October 28, 2008	6	0	0	0	0	0
April 29, 2009	13	4	9	4	11	8
May 21, 2009	12	3	4	2	6	7
June 15, 2009	12	6	8	3	8	6
July 13, 2009	12	0	0	0	0	0
July 27, 2009	12	0	0	0	0	0
September 2, 2009	14	0	0	0	0	0
Oat-wheatgrass with SL soil						
June 16, 2008	10	23	NA	5	NA	27
July 1, 2008	11	8	3	10	1	8
July 14, 2008	11	1	0	0	0	1
August 7, 2008	11	0	0	0	0	0
September 11, 2008	10	2	0	0	0	0
October 20, 2008	5	0	0	0	0	0
May 6, 2009	12	0	0	0	0	0
June 4, 2009	13	0	0	0	0	0
June 25, 2009	12	0	0	0	0	0
July 20, 2009	13	0	0	0	2	2
August 10, 2009	12	0	0	0	0	0
September 1, 2009	15	0	0	0	0	0

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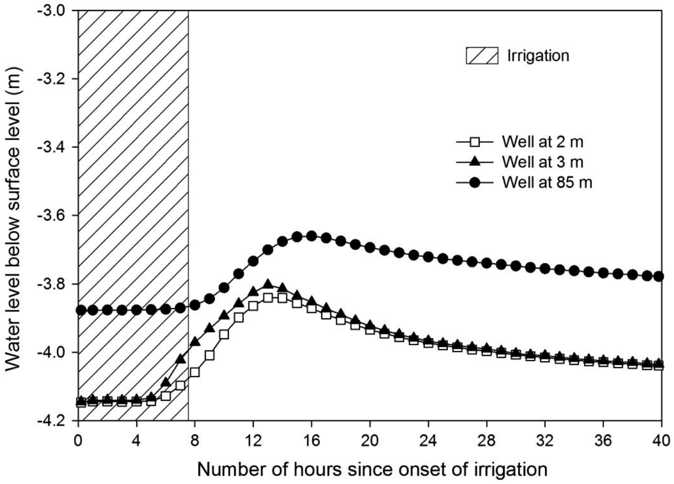

Fig. 5. Water table fluctuations in response to irrigation percolation on June 7, 2006, in three wells located at different distances from the water line in the alfalfa-grass field

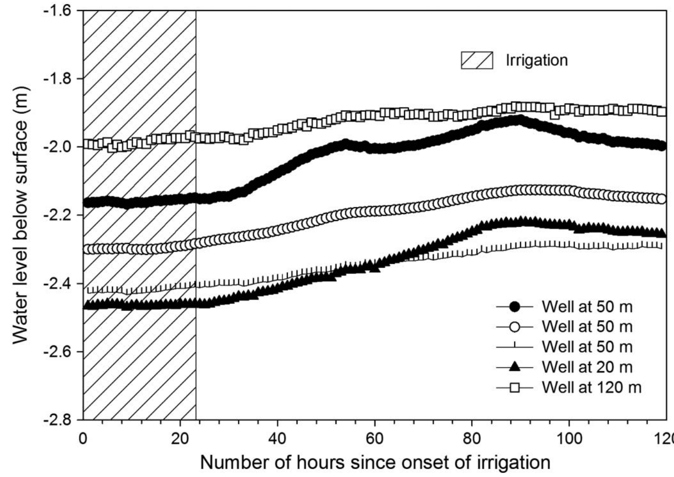

Fig. 6. Water table fluctuations in response to irrigation percolation on June 24, 2008, in five wells located at different distances from the water line in the oat-wheatgrass field

For the alfalfa-grass and apple crop fields, the closer to the water line the wells were located in each field, the greater the aquifer recharge values obtained. Aquifer recharge in the alfalfa-grass field was observed during all irrigation events and ranged from 1 to 126 mm. A relatively rapid water table rise in response to deep percolation inputs was observed in the three wells in the alfalfa-grass field after each irrigation. Fig. 5 shows the irrigation event on June 7, 2006, when peak water table was reached in the three wells monitored in this field only a few hours after the end of irrigation. Aquifer recharge in the apple orchard was observed in the 20-m well during all irrigation events and during all but the last irrigation in the 110-m well. The highest Re value of 230 mm was observed at the 20-m well location (Table 2).

Aquifer recharge in the oat-wheatgrass fields was only observed during a few irrigation events and ranged from 0 to 68 mm among the different well locations (Table 4). The highest values of aquifer recharge in the oat-wheatgrass fields were observed during a 187 mm irrigation on June 24, 2008, in the field with clay loam soil, with Re values ranging from 31 mm at the well located at 120 m distance from the irrigation line to 68 mm in two wells located at 20 and 50 m (Fig. 6). For the rest of the irrigation events, well distance to the water line did not show a significant effect on aquifer recharge in any of the two oat-wheatgrass fields.

Even at the small field scale (≤1 ha), water level fluctuation in response to irrigation percolation can vary considerably, depending on well distance from the water line. This situation is illustrated in Fig. 7, in which a 385 mm irrigation event on May 24, 2006 (Table 2), in the apple orchard resulted in an 820 mm peak water level rise in the well located at 20 m, but it only produced a 288 mm peak rise in the well 110 m away from the water line.

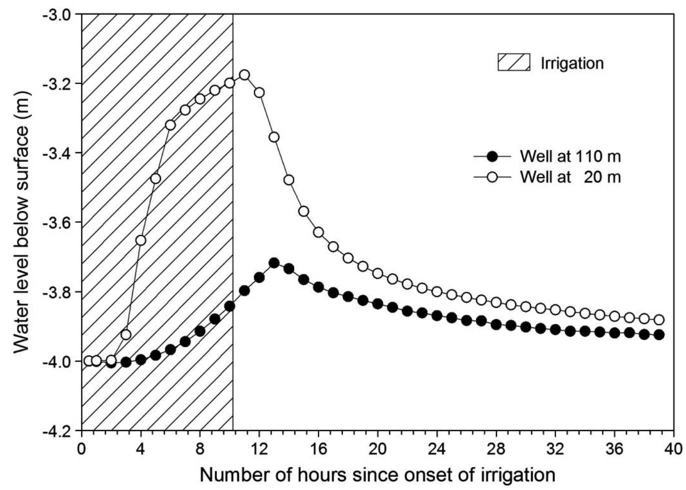

Fig. 7. Water table fluctuations in response to irrigation percolation on May 24, 2006, in two wells located at different distances from the water line in the apple orchard

Table 4. Yearly Estimates of WBM-Re and WTFM-Re for Different Crops and Soil Types from 2005 through 2009

Year	Crop	IRR per year	Average IRR rate (mm h^{-1})	WBM-Re (mm)	WTFM-Re (mm)
2005	Alfalfa-grass (sandy loam)	5	30	385	307
2006	Alfalfa-grass (sandy loam)	4	27	329	157
2006	Apple (clay and sandy loam)	2	57	282	282
2007	Apple (clay and sandy loam)	3	31	242	211
2008	Oat-wheatgrass (clay loam)	6	8	228	53
2008	Oat-wheatgrass (sandy loam)	6	13	247	25
2009	Oat-wheatgrass (clay loam)	6	10	217	18
2009	Oat-wheatgrass (sandy loam)	6	13	219	1
Mean (standard deviation)		5 (1.6)	24 (16.4)	269 (60.1)	132 (124.1)

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Aquifer Recharge: Water Balance Method versus Water Table Fluctuation Method

Crop field-scale aquifer recharge estimates obtained by the WBM were compared to crop field-scale recharge estimates obtained by the WTFM. In general, recharge estimates by the WBM were higher than those estimated by the WTFM. Average recharge per irrigation event estimated by the WBM was 65 mm and ranged from 12 to 165 mm. Average recharge per irrigation event estimated by the WTFM was 28 mm and ranged from 3 to 99 mm.

Also, yearly estimates of aquifer recharge were compared for each crop type. Table 4 shows yearly aquifer recharge estimates by the water balance method (WBM-Re) and by the water table fluctuation method (WTFM-Re) for different year and crop fields. WTFM-Re estimates at each crop field were averaged across wells and added to obtain yearly results that were compared to yearly WBM-Re estimates. Also, the number of irrigation events per year (IRR per year) and the yearly-averaged irrigation rate are shown in Table 4. The IRR rate was calculated based on the total amount of applied irrigation divided by the time of irrigation. In general, yearly WBM-Re values were higher than yearly WTFM-Re values. The highest estimates for aquifer recharge obtained by the WBM-Re (385 mm) and by the WTFM-Re (307 mm) were obtained in the alfalfa-grass field during the 2005 irrigation season, with a total of five irrigation events and an average IRR rate of 30 mm h^{-1} (Table 4).

Potential estimates of aquifer recharge, derived from deep percolation calculations, were higher than actual recharge obtained from shallow groundwater level observations. Annual mean estimates of aquifer recharge of 269 mm obtained by the WBM-Re were greater than annual mean estimates of 132 mm obtained by the WTFM-Re (Table 4). Similar to the current findings, Delin et al. (2000) reported higher estimates of annual aquifer recharge using the water balance method in lowland (400 mm year^{-1}) and upland (250 mm year^{-1}) study sites when compared to hydrograph analysis results (180 mm year^{-1} in lowland and 140 mm year^{-1} in upland). At irrigation rates lower than 15 mm h^{-1}, aquifer recharge estimates with the WBM-Re are considerably higher than those recharge estimates obtained by the WTFM-Re. Healy and Cook (2002) indicated that for long duration and low intensity precipitation events, the water percolation rate may be equal to or less than the rate of drainage away from the recharge area under consideration. The presence of restrictive layers and macropore flow paths (from the rooting system) in some of these experimental fields was observed in previous experiments in these fields, which has been documented by Ochoa et al. (2007, 2009). Therefore, although some of the assumptions of this study were that all water percolating below the top 1 m soil profile would reach the shallow aquifer and that no lateral flow will occur, it is still possible that significant amounts of irrigation water, particularly from smaller application rates, contributed to soil water recharge, dissipated through lateral flow, or reached the water table away from the monitoring wells.

When using the water budget method for estimating aquifer recharge, large errors in estimating the values of the different variables can occur unless the accounting period for the calculations is relatively short. Aquifer recharge by the water balance method is recommended to be estimated daily (Scanlon et al. 2002), or within a week of major infiltration events (Sophocleous 1991). The measurements and estimates for this study of the different water budget variables occurred in a relatively short period of time (24 h after the end of each irrigation event) and the instrumentation was calibrated to the particular soil conditions of each experimental field. However, it is possible that the way the different water budget components are calculated may have contributed to obtaining higher estimates of potential aquifer recharge, when compared to those recharge estimates obtained by the WTFM. For instance, the water budget method assumes that irrigation water is applied uniformly on the soil surface and that the wetting front distributes evenly through the vadose zone and into the aquifer; these assumptions may not fully capture the effects that restrictive layers may have had in slowing percolation water movement through the soil profile.

Water Table Fluctuation Method: Valley Scale

Piezometric level data collected at 28 wells during 2007 through 2009 were used to estimate monthly water table changes and monthly shallow aquifer recharge at the entire valley scale (Table 5). The greatest water level changes were observed during the months of June and July in all three years, with changes in water level values ranging from 550 mm (2007 and 2009) to 790 mm (2008). Monthly aquifer recharge ranged from 25 mm in March of 2009 to 221 mm in June of 2008. The year 2008 showed the highest total aquifer recharge value of 1,350 mm and the year 2007 showed the

Table 5. Monthly Changes in Water Level and Aquifer Recharge Calculated by the Water Fluctuation Method for 2007 through 2009 at the Valley Scale

Month	Δh (mm)	Re (mm)
2007		
January	160	45
February	106	30
March	120	34
April	150	42
May	470	132
June	550	154
July	570	160
August	530	148
September	500	140
October	420	118
November	380	106
December	290	81
Total	3,980	1,114
2008		
January	160	45
February	110	31
March	110	31
April	340	95
May	680	190
June	790	221
July	700	196
August	620	174
September	490	137
October	470	132
November	370	104
December	250	70
Total	4,820	1,350
2009		
January	160	45
February	100	28
March	90	25
April	170	48
May	550	154
June	550	154
July	590	165
August	520	146
September	490	137
October	350	98
November	260	73
December	160	45
Total	3,730	1,044

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lowest total aquifer recharge value of 1,044 mm. In general, the winter months showed the least aquifer recharge values in all three years.

Shallow Groundwater Level Fluctuations

Piezometric level data collected in wells located at different distance from the Alcalde main canal (Fig. 4) were used to characterize the temporal and spatial variability of water table fluctuations at the valley scale. Figs. 8 and 9 show the temporal variability of the shallow groundwater level fluctuations averaged across 28 wells in the valley. For all three years evaluated, a seasonal water table rise and decline pattern was observed (Fig. 8). A closer look at the processes driving the shallow groundwater level fluctuations is shown in Fig. 9. The shallow groundwater table starts rising soon after the canal flow season began on April 7, 2007 and reaches a peak of approximately 0.6 m above baseline at approximately 6 weeks after the onset of the canal flow season. The water table remains approximately 0.5 m above baseline for the rest of the irrigation season, which ends on October 15. This elevated level appears to be driven primarily by deep percolation from irrigation and seepage from the main irrigation canals. After the irrigation season ends, the canal is kept in operation for approximately six more weeks, primarily to provide water for cattle and to flush leaves and debris from the canal. During this fall period when the canal is running, but the fields are not being irrigated, the rise in the water table is primarily driven by seepage from the main canal. A period of delayed return flow can be observed after the end of the canal flow season and before the new irrigation season begins the following year (Fig. 9). During this period, the river essentially acts as a drain, gaining flow from the adjacent elevated water table.

The spatial distribution of shallow groundwater level fluctuations was evaluated based on piezometric level data collected in wells located at different distances from one of the primary irrigation canals. Fig. 10 shows daily averaged water table fluctuations in Transect 1 wells (Fig. 4) from 2007 through 2009. These wells were in dry land (476 m), near canal (3 m), irrigated land (379 m), and near river (749 m) locations. The times of water table response varied across well locations; the well located near the river generally responded first, then the near canal and irrigated land wells, followed by the dryland well. The peak water table rise ranged from 0.26 m (near river well) to 0.41 m (irrigated land well). Sharp water table rises and declines were observed in all except the dryland location well (Fig. 10). Similar patterns of shallow groundwater table fluctuations were observed in Well Transects 2 and 3.

Canal Seepage Contributions to Water Table Fluctuations

Seepage from the primary irrigation canal contributed significantly to raise the local water table, and consequently, to recharge the shallow aquifer in the valley. In a previous study, Fernald et al. (2010) used a water balance approach and estimated that primary canal contributions to shallow aquifer recharge in the valley ranges from 9 to 32% of total canal flow.

Piezometric level and EC data were used to determine the time of arrival of the wetting front to the water table in a well located near the primary irrigation canal. The time of arrival of canal seepage water to the water table, measured at the beginning of each irrigation season from 2005 through 2010, ranged from seven to 12 days, with an average of 10 days. Fig. 11 shows the time of arrival of the wetting front to the well near the canal in Transect

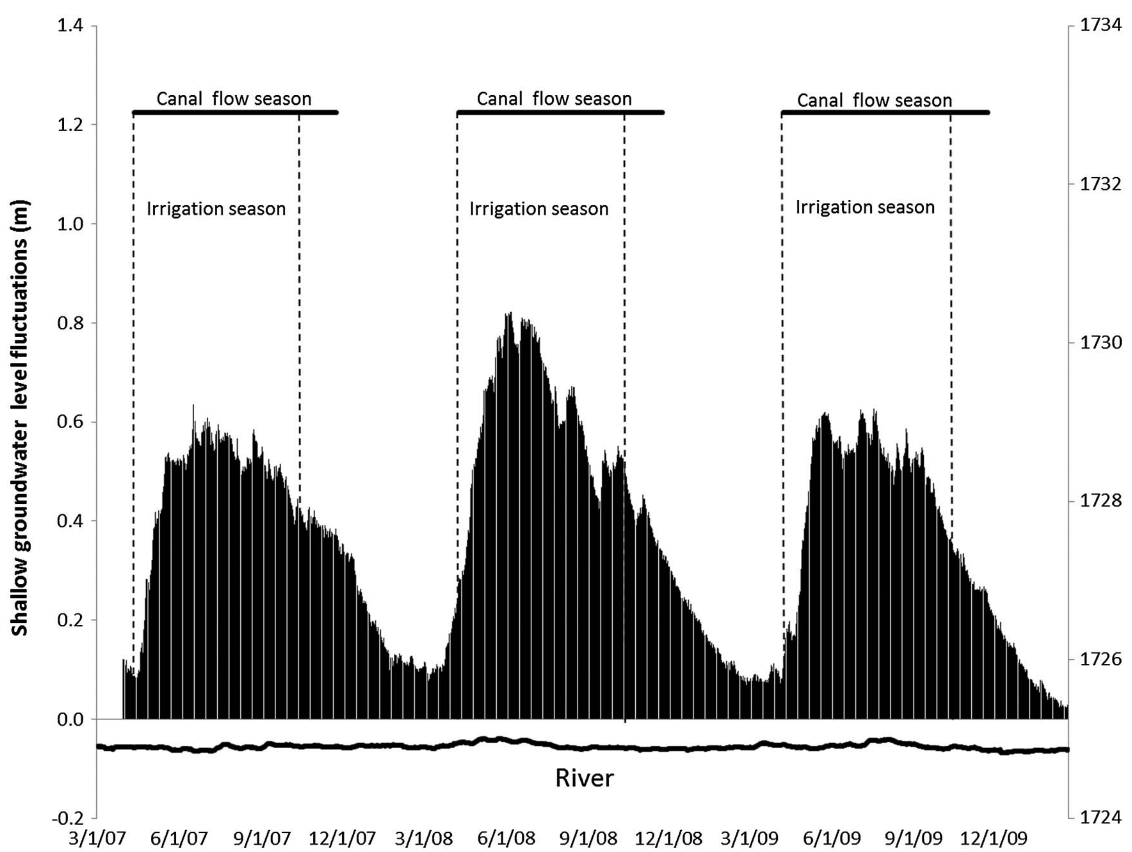

Fig. 8. Shallow groundwater level fluctuations averaged across 28 monitoring wells in the Alcalde-Velarde valley for 2007–2009

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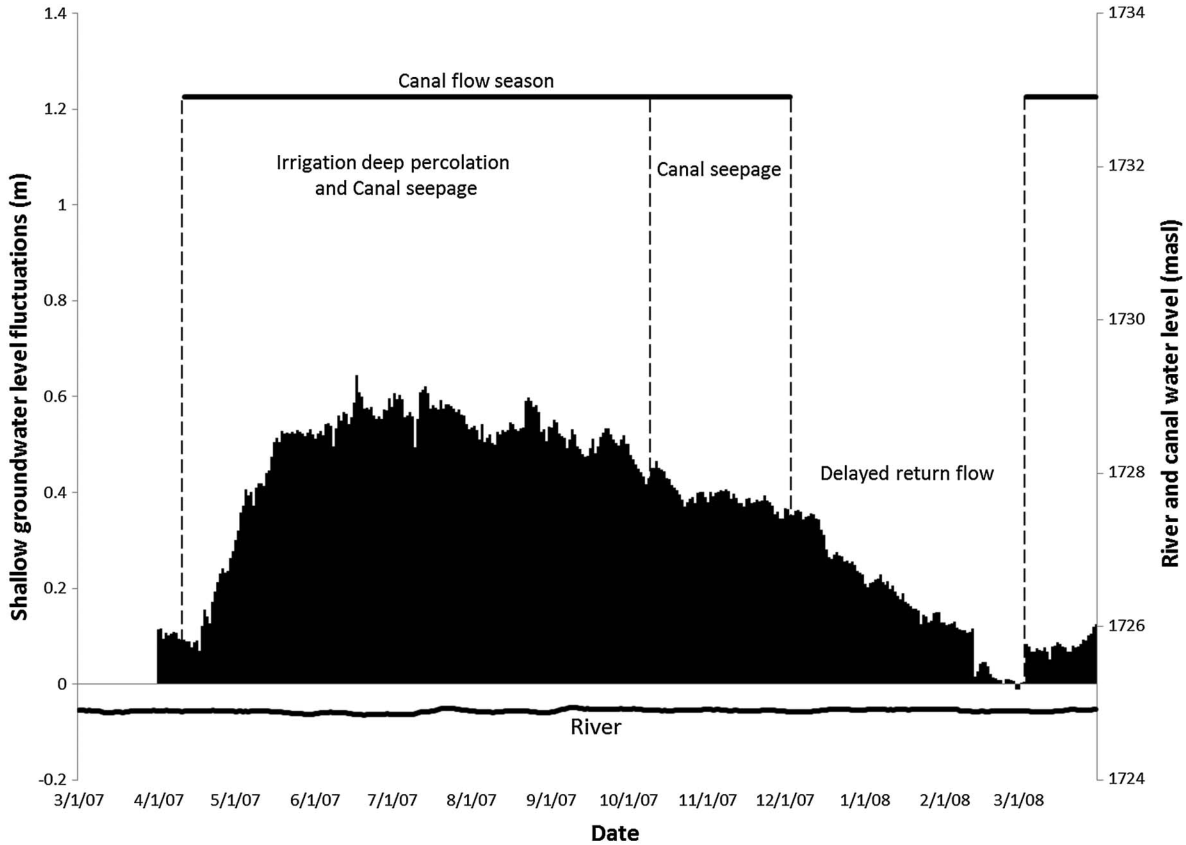

Fig. 9. Shallow groundwater level fluctuations averaged across 28 monitoring wells in the Alcalde-Velarde valley for 2007

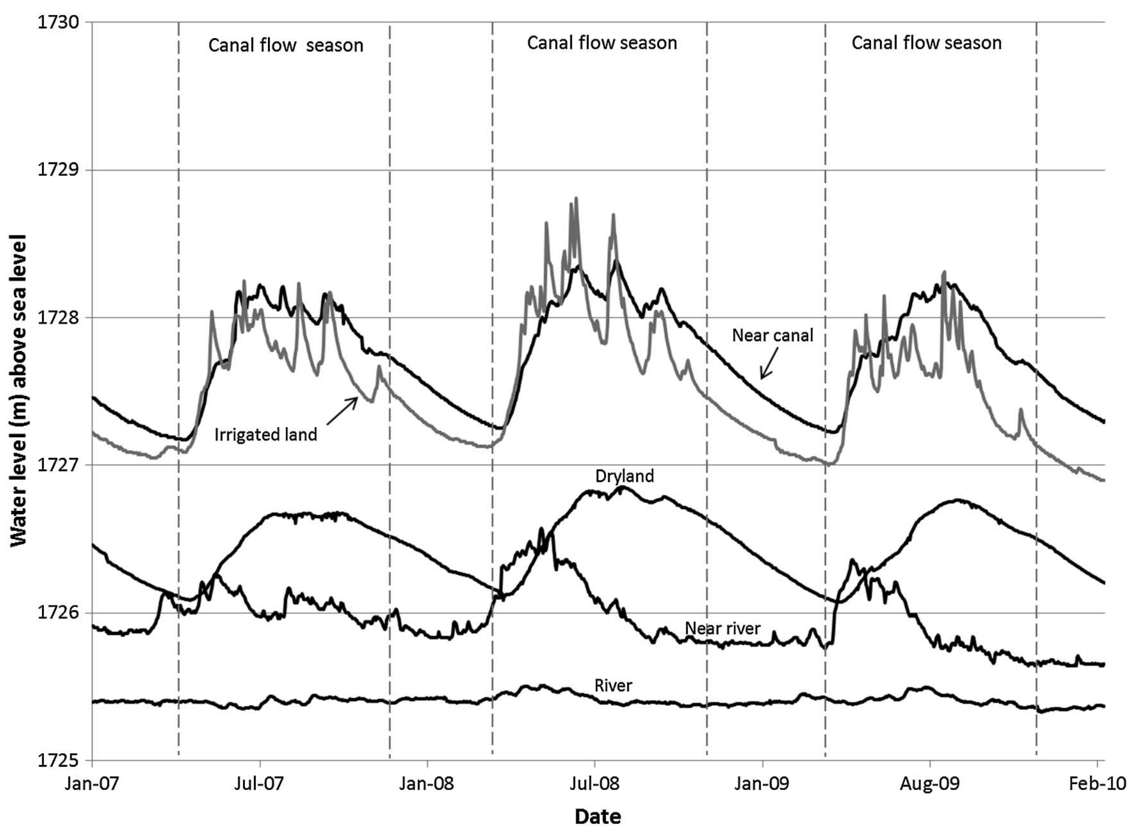

Fig. 10. Water table fluctuations in wells located along Transect 1

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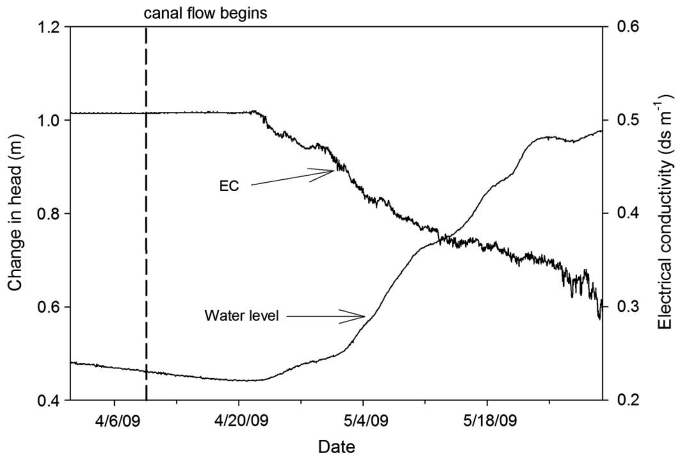

Fig. 11. Shallow groundwater change in head and EC in response to canal seepage inputs in a monitoring well near the main irrigation canal

1, which occurred 12 days after the start of canal flow season in 2009, as indicated by an increase in water head and a decrease in EC. After canal flow season began, the water table time to peak ranged from 63 to 128 days during 2005 through 2010, with rises ranging from 0.8 to 1 m.

Conclusions

It was found that the WBM tends to yield higher estimates of aquifer recharge (269 mm) than the WTFM (132 mm) at the field scale. At the valley scale with the WTFM, it was found that the water table responds seasonally to canal seepage and irrigation percolation. Also, at the valley scale, high amounts of total aquifer recharge were found, with an average of 1,169 mm year^{-1}. These high amounts of aquifer recharge were attributed to a combination of factors, including flood irrigation, highly permeable alluvium soils, and a relatively shallow water table that allows the rapid transport of irrigation water from the soil surface, through the vadose zone, and into the unconfined aquifer. However, the large differences in aquifer recharge estimates obtained for the two different methods evaluated at the field scale indicate that some of the underlying assumptions in use for either method need to be carefully examined when assessing irrigation contributions to the recharge of the shallow aquifer.

Beyond measurements for technique improvement, results of this study add to the understanding of the mechanisms of shallow aquifer recharge and the interactions between surface water and groundwater in a floodplain agricultural valley of northern New Mexico. This study was able to provide enhanced understanding of the timing and magnitude of the shallow aquifer response to direct (irrigation percolation) and localized (canal seepage) inputs. Each year, the shallow aquifer is recharged by irrigation percolation and canal seepage, and water tables rise. In the season without irrigation, the river acts as a drain for the study valley, and shallow groundwater levels drop. The maintenance of yearly aquifer recharge provides many hydrologic ecosystem functions, such as riparian habitat support and river connection to the groundwater. By understanding the spatial distribution of aquifer response to irrigation percolation and canal seepage inputs, one will be better prepared to manage irrigation and maintain aquifer recharge in a future with increased demands for water and drought-constrained supplies. Future work to build on this study might best incorporate river–aquifer interactions, and pumping extraction into a modeling approach will allow the characterization of surface water and groundwater interactions over larger temporal and spatial scales.

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Notation

The following symbols are used in this paper:

ET = evapotranspiration (mm);
IRR = irrigation depth (mm);
P = rainfall (mm);
Re = aquifer recharge (mm);
RO = field runoff (mm);
Sy = specific yield;
Δh = change in water level (mm);
ΔS = change in soil water storage (mm); and
θ = soil water content.

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