DEEP PERCOLATION AND ITS EFFECTS ON SHALLOW GROUNDWATER LEVEL RISE FOLLOWING FLOOD IRRIGATION

C. G. Ochoa, A. G. Fernald, S. J. Guldan, M. K. Shukla

ABSTRACT. *Deep percolation (DP) from irrigation may be important for groundwater recharge in irrigated agricultural river corridors of arid regions, yet few studies of this physiographic setting have characterized both percolation and its direct effects on groundwater levels. The objectives of our study in a sandy loam, flood-irrigated, alfalfa-grass field in northern New Mexico were to (1) compare DP below the 1 m effective root zone based on water balance method (WBM) and Root Zone Water Quality Model (RZWQM) simulations, and (2) characterize effects of DP on shallow groundwater levels. Irrigation water applications were metered, and automated instrumentation measured soil water content and climate data for WBM calculations and RZWQM simulations. Groundwater response was characterized by recorded below-field water levels in four experimental wells. DP varied with initial soil water content and water application amount, ranging from 5 to 18 cm (mean 11.2 ±4.1 SD) with the WBM and from 6 to 17 cm (10.6 ±3.8 SD) with RZWQM (using 0.0005 cm^3 cm^{-3} macroporosity). Across irrigation events, there was high correlation (r = 0.90) between WBM and RZWQM DP. Peak water level response (up to 38 cm) varied from 8 to 16 h after irrigation onset depending on well location and water application amount. Study results show that flood irrigation is a significant source of shallow groundwater recharge. The high correlation between calculated and simulated deep percolation without iterative model calibration indicates that RZWQM can be a useful tool to estimate DP and extend localized field studies to larger spatial scales.*

Keywords. *Deep percolation, Flood irrigation, Root Zone Water Quality Model, RZWQM, Seepage, Shallow groundwater, Time domain reflectometry, Water balance method.*

Deep percolation (DP) below the root zone may provide important hydrologic and ecosystem benefits in irrigated valleys of the arid and semi-arid western U.S. This is particularly true in locations like the Rio Grande Valley in northern New Mexico, where there is low danger of groundwater contamination from irrigation because traditional farming methods involve limited use to no use of agricultural chemicals. Flood irrigation is the most widespread irrigation technique used in agriculture corridors between main irrigation ditches and the Rio Grande. In many of these locations, flood irrigation applications exceed plant consumptive use, and excess water may percolate below the crop root zone and into the shallow groundwater. Deep percolation below the root zone may provide benefits including: recharging the aquifer, delaying return flow to the Rio Grande, diluting contaminants from other sources such as septic tanks, and recharging deep soil water and groundwater that support phreatophytic riparian vegetation with its aesthetic, wildlife, and water quality functions (Fernald and Guldan, 2006).

Percolation below the root zone has been well documented for some crops (O'Connell et al., 2003; Willis et al., 1997), but the link to shallow groundwater is less understood. Previous research has successfully measured and modeled water transport through and below the root zone; for example, temporally separated chloride profiles and mass balance modeling were used to estimate DP in different soils (Willis and Black, 1996). The Root Zone Water Quality Model (RZWQM) has been shown to adequately simulate water content and percolation with proper calibration of key input parameters (Malone et al., 2004). Cameira et al. (1998) used RZWQM to simulate water and nitrate transport in a corn field for different fertilizer applications. Ellerbroek et al. (1998) conducted field and modeling research to evaluate water and pesticide transport into a field soil. Time domain reflectometry (TDR) has been broadly used to measure soil water content in the field. Oliver and Smettem (2005) used field data collected with TDR probes for predicting the water balance in a sandy soil. Vogeler et al. (2001) used TDR probes for collecting soil water content data that were used for predicting water and solute transport through the vadose zone. While these studies and modeling efforts have addressed seepage and water quality effects below the rooting zone, they do not clearly illustrate the entire process of vertical water transport through and below the effective root zone and its effects on water table increases.

Our research sought to characterize the entire profile from surface flood irrigation to root zone to DP to shallow groundwater. In 2004, we initiated a study in flood-irrigated alfalfa-grass (*Medicago sativa* L., various species), one of the

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most widespread crop mixes in the upper Rio Grande in northern New Mexico. Our objectives were to quantify DP under an alfalfa-grass field and to characterize the effects of DP on shallow groundwater levels. We addressed the following study questions:

- What is the calculated amount of DP using a water balance method?
- What is the simulated amount of DP using RZWQM?
- Does calculated DP validate simulated DP?
- What is the nature of the shallow groundwater table increase following flood irrigation?

Materials and Methods

Site Description and Study Design

This study took place at New Mexico State University's Alcalde Sustainable Agriculture Science Center (Alcalde Science Center), 8 km north of Española, New Mexico. The Alcalde Science Center occupies the corridor of agricultural land between the Alcalde main irrigation ditch (Alcalde Ditch) and the Rio Grande. Located at an elevation of 1733 m, the average annual total precipitation for the experimental site is 350 mm, the average maximum annual temperature is 20.1°C, and the average minimum annual temperature is 1.1°C (WRCC, 2006). The science center has 24 ha of irrigated land for research on various forage, fruit, vegetable, and alternative high-value crops using primarily surface flood or furrow irrigation, by far the most common practice in the valley and region. Field study at the Alcalde Science Center took place in a 0.7 ha alfalfa-grass crop field divided into 12 × 190 m strips separated by raised berms. Alfalfa was planted on 15 July 1998 and has been invaded by several species of intermixed grasses since then. The field was flood-irrigated with water diverted from the Alcalde Ditch into a 15 cm diameter irrigation pipe that was used to apply water to the field. During irrigation events, water applications were adjusted across the width of the field to account for small flow path differences and to maintain relatively uniform application. A raised area at the end of the field prevented tail water from leaving the field. The study site overlies an unconfined aquifer, with depth to water table ranging from 3.3 to 5.0 m depending on time of the year. Soil type at the field site is identified as Fruitland sandy loam (USDA, 2006) and is classified as Typic Torriorthents: coarse-loamy, mixed (calcareous) mesic (Alluvial) (Books of the Southwest, 2006).

In July 2004, four 8 × 12 m plots were installed in the middle strip of the experimental field (36.05° N, 106.03° W). The northernmost edge of the first pair of plots (plots 1 and 2) was located 10 m downstream from the irrigation source. The northernmost edge of the second pair of plots (plots 3 and 4) was located 39 m downstream from the irrigation source (fig. 1). We excavated a 1 m square by 1.25 m deep pit in the center of each plot for soil characterization and installation of soil water content sensors. On 10 December 2004, we installed a weather station in the northeast corner of the field to collect rainfall and weather data (air temperature, relative humidity, incoming solar radiation, wind speed and direction).

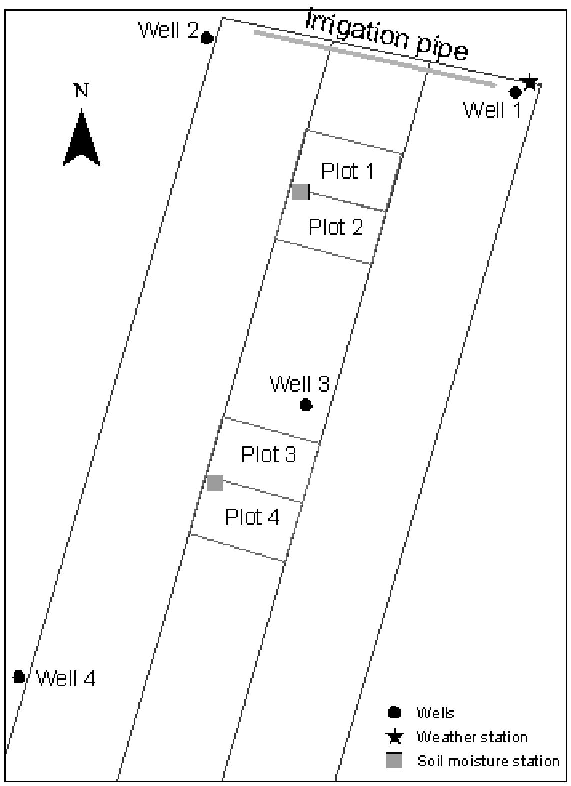

Figure 1. Schematic layout of the deep percolation study site at the Alcalde Science Center.

Field Data Collection of Soil Properties and Water Content

Soil samples for determining soil particle size were collected from two locations in the middle strip of the field (one location in the northeastern half of the field, and the other in the southwestern half) on 4 February 2004. At each location, a JMC Backsaver Handle soil sampler (Clements Associates, Inc., Newton, Iowa) was used to collect three 116 cm long soil samples that were further divided into soil depth increments of 0-30, 30-60, 60-90, and 90-116 cm. Soil samples were pooled by location and depth, air-dried for 48 h, and passed through a 2 mm sieve. Using a fractionator, each soil sample was subdivided into two subsamples. Soil particle size was determined with a laser diffraction particle size analyzer (LS230, Beckman Coulter, Inc., Fullerton, Cal.) using about 0.3 g of soil from each subsample. The results obtained from each subsample were averaged to yield a single particle size distribution for each soil depth.

Immediately prior to the soil water content sensor installation in each pit on 14 July 2004, core soil samples for determining soil bulk density (ρ_b) were collected from the pits. A soil core sampler was used to collect three core samples (5 cm diameter × 3 cm length) at 12.5, 37.5, 62.5, 87.5, and 112.5 cm depths (fig. 2). Soil core samples were oven-dried at 105°C for 48 h and weighed. The ρ_b was calculated using the procedure suggested by Blake and Hartge (1986).

Soil samples for calculating gravimetric water content (*W*) of soil were collected from plots 2 and 4 before and after the irrigation event on 1 September 2005. At each plot, three soil samples were taken from each of five progressively deeper 25 cm depth increments. Soil samples were weighed immediately after the collection and then oven-dried at 100°C for 48 h. The oven-dried samples were re-weighed, and gravimetric water content was calculated using the procedure of Gardner (1986). The gravimetric water content values were multiplied by soil bulk density to obtain the volumetric water content ($\theta = W \times \rho_b$).

In situ volumetric water content of soil was measured using TDR systems (Campbell Scientific, Inc., Logan, Utah). Each TDR system was powered with a 12 V deep-cycle battery and included one CR10X datalogger, two SDMX50 multiplexers, one TDR 100 cable tester, and ten CS-605 soil water content probes. Nests of five probes each were installed in the upper 125 cm of the soil profile in all four pits excavated in the plots (fig. 2). For purposes of installing the TDR waveguides, we divided the 125 cm soil profile into five depth increments of 25 cm each. The 30 cm long TDR probe waveguides were installed vertically at a 16° angle so that the length of the probe corresponded to each 25 cm depth of soil. Soil volumetric water content data were collected hourly beginning after probe installation in July 2004. Beginning 19 May 2005, the first irrigation event of the 2005 irrigation season, soil water content data were collected every 3 min during irrigation events and every 60 min thereafter.

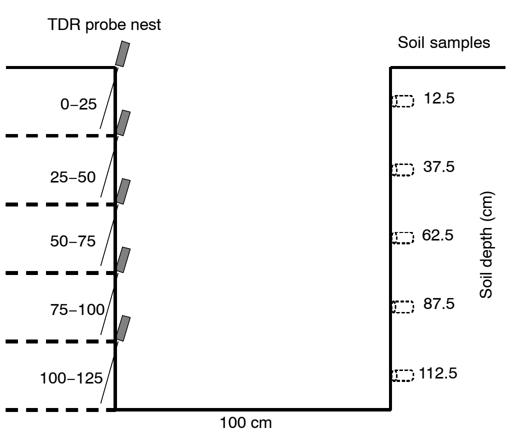

Figure 2. Schematic of TDR probe nest installation and bulk soil sample collection in one excavated pit.

Measurements of soil water content using TDR technology are based on the unique electrical properties of water. The dielectric constant of water (about 80) is much greater than that of the remaining soil solid components (from 2 to 7) and of air (1). Therefore, measuring the dielectric constant of soil gives a reliable estimate of the water content in the soil (Topp, 1993). The conversion of the dielectric constant (*Ka*) into soil volumetric water content (θ) is obtained using a third-degree polynomial equation (Topp et al, 1980):

$$\theta = 5.03\times10^{-2} + 2.92\times10^{-2} Ka - 5.5\times10^{-4} Ka^2 + 4.3\times10^{-6} Ka^3 \quad (1)$$

Topp's equation has shown a close correlation between θ and *Ka* for a wide variety of soils (Dalton, 1992), although specific calibration may be required for some soil classes (Teixeira et al., 2003).

We used the gravimetric method to calibrate the soil volumetric water data measured by the TDR probes. We developed an equation for calculating a correction factor (f_c) for each soil depth:

$$f_c = \left[\left[(\theta_b\_TDR) - (\theta_b\_Grav)\right] + \left[(\theta_a\_TDR) - (\theta_a\_Grav)\right] \right] \div 2 \quad (2)$$

where

- f_c = correction factor ($cm^3\ cm^{-3}$)
- θ_b_TDR = soil volumetric water content before irrigation measured with TDR probe ($cm^3\ cm^{-3}$)
- θ_b_Grav = soil volumetric water content before irrigation using gravimetric method ($cm^3\ cm^{-3}$)
- θ_a_TDR = soil volumetric water content after irrigation measured with TDR probe ($cm^3\ cm^{-3}$)
- θ_a_Grav = soil volumetric water content after irrigation using gravimetric method ($cm^3\ cm^{-3}$).

The f_c was obtained for each soil depth increment of 25 cm in each plot, and it was subtracted from the TDR-measured soil volumetric water content for the corresponding soil depth and plot.

Water Balance Method (WBM) to Calculate Deep Percolation using Field-Measured Data

A water balance method was used for calculating DP below the upper 1 m on a daily basis, the upper 1 m being designated as the effective root zone. We calculated DP after each irrigation event using a modified equation described by Lal and Shukla (2004). Precipitation did not occur during any of the irrigation events, and runoff was considered negligible; thus, DP was calculated using the following equation:

$$DP = IRR + SWC_i - SWC_{fc} - ET \quad (3)$$

where

DP = deep percolation (cm day^{-1})

IRR = amount of water applied as irrigation (cm)

SWC_i = soil initial water content $[\bar{\theta}_i \times 100]$ (cm)

SWC_{fc} = soil water content at field capacity $[\bar{\theta}_{fc} \times 100]$ (cm)

ET = amount of evapotranspiration estimated for a given day (cm).

DP was calculated as the total amount of water passing below the 1 m rooting zone after each irrigation event. The amount of water applied (IRR) was calculated based on flow rate Q (m^3 h^{-1}) measured by a propeller flowmeter (McCrometer, Inc., Hemet, Cal.) mounted in a 20 cm inner diameter metal pipe, time of irrigation t (h), and total area of the field A (m^2), as IRR = $(Q \times t)/A$. Time of standing irrigation water was measured at each plot. The initial soil volumetric water content (θ_i) data collected with the TDR sensors at every 25 cm soil depth in the upper 1 m and at all four plots were averaged to obtain the average soil water content ($\bar{\theta}_i$) of the different depths. The corresponding $\bar{\theta}_i$ was multiplied by 100 cm to obtain SWC_i. The soil volumetric water content at field capacity (θ_{fc}) data collected with the TDR sensors at every 25 cm soil depth in the upper 1 m and at all four plots were averaged to obtain the average soil water content at field capacity ($\bar{\theta}_{fc}$) of the different depths. The corresponding $\bar{\theta}_{fc}$ was multiplied by 100 cm to obtain SWC_{fc}. The calculated SWC_i and SWC_{fc} were assumed to be representative of the entire field soil water content. The evapotranspiration (ET) value for the corresponding day was obtained from potential evapotranspiration (PET) values calculated from data collected in a nearby weather station located at the Alcalde Science Center (NMCC, 2006). All values in equation 3 are expressed in cm, assuming a 100 cm depth for the effective rooting zone.

Deep Percolation Using RZWQM

We used RZWQM version 1.3.2004.beta to estimate DP below the 1 m root zone from 1 January to 31 December 2005. RZWQM is an integrated physical, biological, and chemical process model developed by the USDA-ARS to simulate crop growth and nutrient, pesticide, and water movement through the rooting zone (Ahuja et al., 2000). The model is divided into six main processes, namely physical, chemical, nutrient, pesticide, plant growth, and management. For this research, we focused on the physical processes of the model, which include water infiltration through the soil matrix and macropores, soil water redistribution, plant water uptake, and evapotranspiration. Based on the multi-depth data collection configuration we had in place for collecting soil water content and after observing relatively little soil color or soil texture difference between soil depths, we conducted a straightforward comparison to determine if we needed to continue using the multi-depth approach or change to a 1 m homogeneous soil profile approach. We conducted an analysis of means for determining if there was a significant difference between soil initial water content and soil water content at field capacity for different soil depths. In conducting the analysis of means, we performed an analysis of variance (ANOVA) with Tukey's HSD test ($P \leq 0.05$) using SAS version 9.1 (SAS, 1989).

RZWQM Input Parameters

In conversations with the model developers and based on the hydrological processes (infiltration, water redistribution, and evapotranspiration) used for simulating DP, we decided to run the model without calibration for specific parameters and with the minimum required data suggested by Ahuja et al. (2000). As part of the initial parameterization, RZWQM requires the description of the crop selection, in this case alfalfa. In addition, the model requires breakpoint rainfall, averaged daily meteorology, crop residue, field-averaged water applied, soil properties, and soil water content data (Cameira et al., 1998). The model can be initialized with values for texture and bulk density as the minimum soil properties input data (Abrahamson et al., 2005). The initial parameter values used in RZWQM were entered based on field measurements, field experience, and model default values.

Using field measurements, we entered values for total rainfall, weather data, crop residue, water applied, and soil physical and hydraulic properties. Total rainfall and weather data (minimum and maximum air temperature, wind run, shortwave radiation, and relative humidity) were collected hourly at the weather station installed on-site and were converted to daily averages. Crop residue samples after harvest were collected twice (10 June and 15 July 2005) during the study period. Residue samples were collected using five placements of a 1 × 1 m frame in randomly selected areas near the soil water content sensors. Samples were weighed, and the average of all sample weights over the two dates was used as the model input crop residue (kg h^{-1}). The total amount of water applied for each irrigation event was entered using the "specific dates" tab in the "irrigation management" option under "management practices" input parameters. The total amount of water applied over five irrigation events in the 2005 season was 118.1 cm. Most soil physical and hydraulic parameter values used in the model were obtained from soil samples collected and from TDR measurements of soil water content recorded at the study site. Four soil depths of 25 cm each were parameterized based on measured soil properties. Measured soil properties for each soil depth were bulk density and fractions of sand, silt, and clay. Values of initial soil water content for different depths were obtained by averaging the TDR-measured soil water content on 1 January 2005 in plots 3 and 4. Field capacity water content values used in the "soil hydraulics" part of the model were averaged for the five irrigation events from TDR-measured soil water content 24 h after an irrigation event.

Values entered based on field experience were height of alfalfa at cutting (40 cm), height after cutting (5 cm), the earliest day when alfalfa would come out of dormancy (16 March), height of alfalfa the first day of the year (10 cm), and harvesting dates (10 June, 15 July, and 23 Sept.).

Macropores

Macropores or biopores are formed by the interactions of the soil and the biota (i.e., decayed root channels, living roots, etc.), and they are influenced by soil management practices (Lal and Shukla, 2004). Macropores can play an important role in soil water transport (Cameira et al., 2000). Preferential flow increases in alfalfa fields have been reported by Meek et al. (1990), who found high infiltration in a 5-year-old alfalfa field due to an extensively well-developed macropore system primarily due to the decomposition of a long and dense rooting system. Alfalfa was planted in our field in 1998, and no subsequent mechanical manipulation of the soil was carried out. Therefore, there is a strong likelihood of a well-developed macropore system at the experimental site (Rasse et al., 2000). The model was run with and without the macropores present in the "soil physical properties" option selected. Since exact dimensions of macropores were unavailable, model default values for total macroporosity were used.

RZWQM Sensitivity Analysis

We conducted a sensitivity analysis of RZWQM input parameters (i.e., total irrigation, initial soil water content, soil bulk density, macroporosity, and saturated hydraulic conductivity). We used the equation described by Walker et al. (2000) to calculate sensitivity index (*S*) for the selected parameters and to determine the influence of individual parameters on average DP for the simulation period:

$$S = \frac{(O_2 - O_1)}{(I_2 - I_1)} \frac{I_{avg}}{O_{avg}} \tag{4}$$

where

S = relative sensitivity index

I_1 and I_2 = minimum and maximum value tested for a given parameter

I_{avg} = average value of I_1 and I_2

O_1 and O_2 = RZWQM output values corresponding to I_1 and I_2

O_{avg} = average value of O_1 and O_2.

Individual variations of input parameters over an expected range of values were made to obtain different output values for DP. Parameter values and DP output values were used in the equation for obtaining the corresponding relative sensitivity index.

The greater the sensitivity index is for a given parameter, the greater the impact on the DP. A positive value of *S* means that the input parameter and output value are positively related. A negative value indicates that the input parameter and the output value are inversely related (Walker et al., 2000).

Comparison of WBM to RZWQM

We compared DP results calculated by WBM to DP results simulated by RZWQM both with the macropores and without the macropores option selected. Farahani et al. (1999) stated that simulated values within 10% to 20% of measured values are an acceptable level of model error. Hanson et al. (1999) reported that field measurement errors are normally greater than 10% and that simulated data cannot be matched closer than that. Different degrees of error can be obtained by calibrating or not calibrating RZWQM. For example, Hanson et al. (1999) reported degrees of error that ranged from −18% to 88% for selected field indicator variables (e.g., total biomass, yield, etc.) before calibrating RZWQM for the generic crop production component at different study sites. Results improved to a 5% to 20% degrees of error after calibration. Abrahamson et al. (2005) used sensitivity analysis and calibrated RZWQM with and without macropores until predicted values of tile drainage and leached nitrate were within 15% of measured values.

Since our goal was not to calibrate RZWQM but rather to test it with the minimum input data and under no calibration conditions, we did not set a degree of error target.

We used a percentage difference equation (*%D*) similar to that used by Oliver and Smettem (2005) to describe the degree of error between RZWQM-predicted and WBM-calculated results:

$$\%D = \frac{(\text{WBM}_{\text{DP}} - \text{RZWQM}_{\text{DP}})}{(\text{WBM}_{\text{DP}})} * 100 \tag{5}$$

where

$\%D$ = percentage difference

WBM_{DP} = deep percolation calculated by WBM

RZWQM_{DP} = deep percolation predicted by RZWQM.

Using *%D*, we compared results calculated by the WBM to those simulated by the uncalibrated RZWQM with and without macropores.

Shallow Groundwater Response to Deep Percolation

During the 2005 irrigation season, we installed three galvanized 5 cm diameter driven-point wells (fig. 1): well 1 on the northeast corner, well 4 on the west boundary of the field, and well 3 in the middle strip of the field. We installed these wells based on groundwater flow paths at the Alcalde Science Center, as reported by Fernald and Guldan (2006), that show that groundwater flow runs from northeast to southwest when water is not running in the Alcalde main irrigation ditch and that flow paths orient more westward towards the river during the irrigation season. These wells were 6.1 m deep with a 1.2 m screen. Water measurements were also made in a previously installed PVC (polyvinyl chloride) well on the northwest corner (well 2) (refer to fig. 1). This well was 10.6 m deep 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.

The wells were installed at different distances from the irrigation source and in general alignment with the flow paths reported by Fernald and Guldan (2006). Wells 1 and 2 were the closest, located 2.0 and 3.5 m away from the irrigation source, respectively. Well 3, in the middle strip, was 40 m away from the irrigation source. Well 4 was the farthest at 85 m from the irrigation source. The pre-irrigation shallow groundwater gradient was 0.22% from well 1 (northeast corner) to well 2 (northwest corner) and 0.18% from well 2 to well 4 (west edge).

After installation, the wells were geo-positioned using a Pro XRS (Trimble Navigation, Ltd., Sunnyvale, Cal.) GPS unit and were surveyed for elevation using a GTS 226 total station (Topcon Positioning Systems, Pleasanton, Cal.). All wells were equipped with pressure transducers (Campbell Scientific, Inc., Logan, Utah) attached to dataloggers and programmed to collect hourly water level data. Water level data were entered into a spreadsheet to characterize water level fluctuations during specific irrigation events and throughout the irrigation season. In order to limit nearby-field irrigation effects on groundwater level readings at the study site, we avoided irrigating these nearby fields for at least 24 h prior to irrigation of the study field. From the water level data collected at the different wells, we calculated the peak water level and the time to peak at each well after

Table 1. Soil physical properties used in RZWQM.

Depths (cm)	$\bar{\theta}_i$ ($cm^3 cm^{-3}$)	$\bar{\theta}_{fc}$ ($cm^3 cm^{-3}$)	ρ_b ($g\ cm^{-3}$)	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)
0-25	0.172	0.321	1.42	660	311	29
25-50	0.180	0.256	1.48	660	310	30
50-75	0.187	0.259	1.37	697	276	27
75-100	0.175	0.272	1.50	791	188	21
Mean[a]	0.179	0.277	1.44	702	271	27
SD	0.01	0.03	0.06	67.84	57.84	4.03

[a] Mean and standard deviation (SD) are estimated across depths.

irrigation water was applied on the experimental field. The peak water level was calculated as the difference between the baseline water level and the maximum rise reached after each individual irrigation event. Time to peak was calculated as the difference between the time when the water level started rising and the time when peak water level was reached.

Results and Discussion

Soil Physical Properties

Soil properties measured in the 1 m soil profile varied with each 25 cm depth (table 1). In general, the sand content increased and silt and clay contents decreased with soil depth. The highest content of sand (791 g kg^{-1}) and the lowest content of silt (188 g kg^{-1}) and clay (21 g kg^{-1}) were observed at the 75-100 cm depth. The lowest values of $\bar{\theta}_i$ were obtained at the 0-25 cm (0.172) and 75-100 cm (0.175) depths. In the case of the 0-25 cm depth, the low value of $\bar{\theta}_i$ was probably due to greater evaporative losses from the soil surface. At the 75-100 cm depth, the low $\bar{\theta}_i$ value obtained was attributed to a coarser soil texture.

Deep Percolation Using the WBM

Results obtained for selected parameters used in calculating DP varied for the different irrigation events (table 2). The time of irrigation (*t*) ranged from 6.9 to 8.7 h. The lowest SWC_i value (12.4 cm) was obtained on 19 May 2005, at the beginning of the irrigation season. The highest SWC_i value (19.3 cm) was obtained on 6 July 2005. The average SWC_i for the five irrigation events was 16.3 cm. The total amount of water applied varied among irrigation events and ranged from 19.8 to 29.8 cm. Soil water content at field capacity (SWC_{fc}), 24 h after irrigation events, remained relatively constant at around 28.0 cm. Estimated ET ranged from 0.5 to 0.8 cm. Calculated DP ranged from 5.3 to 18.0 cm depending on the amount of water applied. The highest DP (18.0 cm) corresponded to the highest amount of water applied (29.8 cm) for the irrigation event of 27 July. The lowest DP (5.3 cm), obtained after the first irrigation event of 21.6 cm on 19 May, corresponded to the lowest SWC_i of 12.4 cm. A high correlation (r = 0.76) was observed between IRR and DP and, similar to that reported by Willis et al. (1997), the more water applied, the more DP obtained.

Table 2. Deep percolation by the water balance method (WBM).

Date (2005)	*t* (h)	SWC_i (cm)	IRR (cm)	SWC_{fc} (cm)	ET (cm)	DP (cm)
19 May	7.0	12.4	21.6	28.0	0.7	5.3
15 June	7.9	14.0	25.0	27.8	0.8	10.4
6 July	6.9	19.3	21.9	28.0	0.7	12.4
27 July	8.7	17.1	29.8	28.3	0.6	18.0
1 Sept.	7.3	18.7	19.8	27.8	0.5	10.1

Deep Percolation using RZWQM

The analysis of means for initial soil water content and field capacity showed significant differences between soil depths. For initial soil water content, the only significant difference ($P \leq 0.05$) was between the 25-50 cm and 75-100 cm depths (table 3). Mean soil water content at field capacity for the 0-25 cm depth was higher than for the 25-50, 50-75, and 75-100 cm depths. Therefore, we decided to use a multi-depth soil profile (with four depths) for model simulations.

Sensitivity Analysis for RZWQM

Sensitivity analysis of input parameters for RZWQM showed that for the simulation of DP, total amount of irrigation was the most sensitive parameter (S = 0.99) (table 4). A strong influence of the amount of water applied on DP was also reported by Ellerbroek et al. (1998). The remaining parameters did not show substantial effects on estimates of deep percolation (table 4). Low influence of saturated hydraulic conductivity on DP was also reported by Oliver and Smettem (2005) and Ellerbroek et al. (1998).

Comparison of WBM to RZWQM

Simulated DP results by RZWQM with macropores (10.6 ±3.8 cm) more closely matched WBM estimates (11.2 ±4.1 cm) of DP than when macropores were not included in RZWQM simulations (8.2 ±3.1 cm) (table 5). Importantly, we did not calibrate RZWQM to improve the match between simulated and calculated DP. Deep percolation results simulated by RZWQM without macropores were consistently underpredicted, as much as −41.6% *D*, when compared to results obtained by WBM. The *%D* of deep

Table 3. Results for initial soil water content and field capacity analysis of means.[a]

Soil Depth (cm)	Average Soil Initial Water Content ($cm^3\ cm^{-3}$)			Average Soil Water Content at Field Capacity ($cm^3\ cm^{-3}$)		
	n	Mean[b]	SD	*n*	Mean[b]	SD
0-25	20	0.150 abc	0.036	14	0.321 b	0.021
25-50	20	0.129 c	0.046	14	0.256 a	0.027
50-75	16	0.162 abc	0.048	11	0.259 a	0.037
75-100	16	0.179 ab	0.038	11	0.272 a	0.019

[a] Average soil initial water content and average soil water content at field capacity are the means obtained for the five irrigation events.

[b] Means followed by the same letter are not significantly different by Tukey's HSD at $P \leq 0.05$.

Table 4. Sensitivity analysis results of selected parameters used in RZWQM.

Parameter Description	Base Value	Input Values I_1	I_2	I_{avg}	Output Values O_1	O_2	O_{avg}	Sensitivity Index (S)
Total amount of irrigation (cm)	118.10	0.00	149.00	74.50	0.00	0.29	0.14	0.99
Soil bulk density (g cm^{-3})	1.44	1.35	1.55	1.45	0.20	0.20	0.20	−0.05
Saturated hydraulic conductivity (cm h^{-1})	2.78	1.50	15.00	8.25	0.21	0.20	0.21	−0.03
Total macroporosity (cm^3 cm^{-3})	0.0005	0.00	0.001	0.0005	0.18	0.20	0.19	0.06
Initial water content (cm^3 cm^{-3})	0.15	0.05	0.25	0.15	0.20	0.21	0.20	0.05

Table 5. Calculated (WBM_{DP}) and modeled ($RZWQM_{DP}$) deep percolation.

Date (2005)	WBM_{DP} (cm)	$RZWQM_{DP}$ with macropores (cm)	%D	$RZWQM_{DP}$ with no macropores (cm)	%D
19 May	5.3	6.6	24.5	4.2	−20.8
15 June	10.4	11.7	12.5	9.3	−10.6
6 July	12.4	9.8	−21.0	8.3	−33.1
27 July	18.0	17.3	−3.9	13.4	−25.6
1 Sept.	10.1	7.4	−26.7	5.9	−41.6
Mean	11.2	10.6		8.2	
SD	4.1	3.8		3.1	

percolation simulated values ($RZWQM_{DP}$) with macropores (−26.7% to 24.5%) were slightly beyond the range of values that Farahani et al. (1999) considered acceptable. RZWQM simulations with the macropores option overpredicted (24.5% and 12.5% *D*) DP for the first two irrigation events and underpredicted (−21.0%, −3.9%, and − 26.7% *D*) DP for the remaining three events.

Model results, based on field-averaged water application depth, were consistent with water balance results based on individual plot measurements. Time of standing irrigation water (intake opportunity time) averaged across the four plots was slightly higher than the actual time of irrigation application, ranging from 4 to 33 min longer than irrigation time depending on irrigation event. Intake opportunity times at the end of the field and averaged over the entire field were lower than irrigation time. At the field scale, lower intake opportunity time at points other than the measuring points would suggest overestimation of the amount of water applied in the model. On the other hand, at the point scale, topographic differences in the soil surface, particularly elevated soil causing lower intake opportunity time above well 4, suggest variability between points and no systematic under- or overestimation of infiltration. Considering the variability in infiltration at different points along the field and the close match between measured and modeled infiltrated water at the study plots, the field-averaged water applied in the model was appropriate for simulating water distribution and infiltration in the study field.

Shallow Groundwater Response to Deep Percolation

The amount of change in water level elevations due to DP seemed to be influenced largely by the amount of water applied (table 6). The highest peak water level (38 cm) was observed in well 1 after the irrigation event of 27 July, when the highest amount of water (30 cm) was applied. In addition, the change in water level elevations appeared to be influenced to a certain extent by antecedent soil moisture. This is illustrated by data from wells 1 and 2 for the irrigation events of 19 May and 6 July, when similar amounts of water were applied (22 cm). SWC_i was 12.4 cm before the 19 May irrigation event and 19.3 cm before the 6 July irrigation event (refer to table 2). The peak water levels reached after applying 22 cm of water to soil with smaller SWC_i (19 May) were 14 cm and 16 cm in wells 1 and 2, respectively; however, after applying 22 cm of water to soil with larger SWC_i (6 July), peak water levels reached 36 cm and 29 cm in wells 1 and 2, respectively. The distance from well to irrigation source for each well was also important for determining the peak water level and time to peak water level during irrigation. The smallest increase in peak water level and the greatest time to peak was observed in well 4 (table 6), which was the farthest well (85 m) from the irrigation source. Soil surface topographic differences appeared to influence intake opportunity time for some measuring points along the field. For example, the well 4 location had a decreased intake opportunity time because it was installed farther from the irrigation source and because it was located in a more elevated portion of the field, resulting in less exposure to water during irrigation events compared to the other three well locations.

The beginning of water level increase varied for the different wells, as illustrated during the irrigation event of 15 June 2005 (fig. 3). Water levels started to increase around mid-irrigation time and were first observed in wells 1 and 2,

Table 6. Shallow groundwater response to different irrigation events measured at different wells.[a]

Date (2005)	Total Water Applied (cm)	Well 1 Peak Water Level (cm)	Well 1 Time to Peak (h)	Well 2 Peak Water Level (cm)	Well 2 Time to Peak (h)	Well 3 Peak Water Level (cm)	Well 3 Time to Peak (h)	Well 4 Peak Water Level (cm)	Well 4 Time to Peak (h)
19 May	22	14	15	16	18	NA	NA	13	25
15 June	25	35	9	21	11	16	12	9	16
6 July	22	36	11	29	12	NA	NA	NA	NA
27 July	30	38	10	30	13	NA	NA	22	16
1 Sept.	20	24	8	17	11	NA	NA	13	13
Mean	23.8	29.4	10.6	22.6	13.0	NA	NA	14.3	17.5
SD	3.9	10.2	2.7	6.6	2.9	NA	NA	5.5	5.2

[a] NA = data not available.

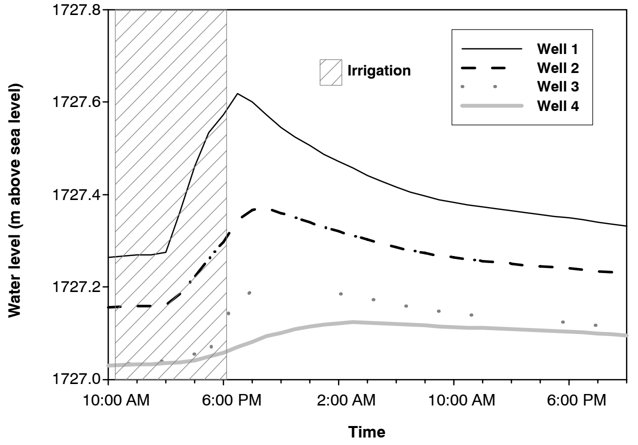

Figure 3. Water level fluctuations in four experimental wells in response to the irrigation event of 15 June 2005.

followed by wells 3 and 4. A similar trend among wells was observed in peak water level and time to peak for the same irrigation event (refer to table 6), where peak water level ranged from 9 to 35 cm and time to peak ranged from 9 to 16 h.

The well water level fluctuations during the 2005 irrigation season are presented in figure 4. Water levels in all wells had increased even before the first irrigation (I) event on 19 May 2005. Because no irrigation in nearby fields was applied before the first irrigation event, the increase in water level prior to this first event can be attributed to seepage from the main irrigation ditch (Fernald and Guldan, 2006) and possibly to irrigation events in more distant fields at the Alcalde Science Center. A rapid increase-decrease in water level in all four wells was observed after each of the five on-field irrigation events. In addition, the water level data reveal that water level increased after nearby fields (Ia) were irrigated, but the increase in water level following irrigation and the decrease in water level after reaching peak water levels was generally not as rapid as for the distinct study field (I) irrigation events.

Water level fluctuations following the five on-field irrigation events in 2005 were consistent with calculated and simulated DP below the 1 m effective root zone (fig. 5). For the example of well 2 (fig. 5), water table fluctuation showed

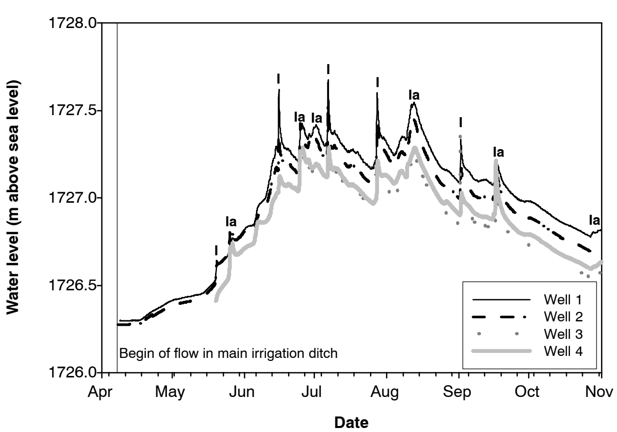

Figure 4. Well water level response to on-field irrigation (I) and nearby field irrigation (Ia) during the 2005 irrigation season.

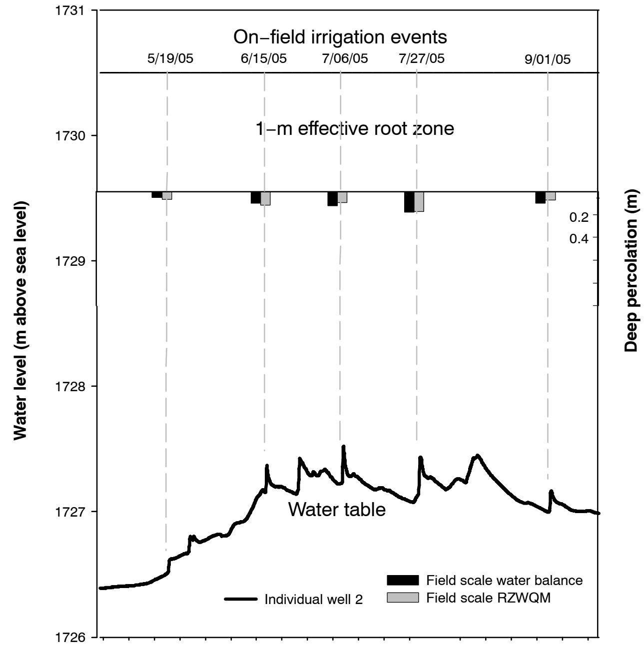

Figure 5. Shallow groundwater response to calculated (water balance method) and simulated (RZWQM) deep percolation in well 2 after five on-field irrigations during the 2005 season.

a clear response to DP after on-field irrigation that depended on the amount of water applied and initial soil water content (refer to table 2). A rapid and significant water level response was observed in conjunction with the different irrigation events at the 0.7 ha alfalfa-grass field. We attribute the rapid response of shallow groundwater to deep percolation to three particular features of our study site: a relatively shallow (3.3 to 5.0 m deep) water table, highly permeable sandy loam soil, and an aging alfalfa field likely to promote development of macropores.

Conclusions

We found close agreement between calculated deep percolation using the water balance method and simulated deep percolation using RZWQM including macropores. Deep percolation was positively related to irrigation application amount. Antecedent soil water content also had an effect on deep percolation, with less deep percolation under drier antecedent soil water content conditions. Increases in measured water level were observed both after on-field irrigation events and after nearby field irrigation events. Water level response to irrigation was more rapid in wells closer to the irrigation source than in wells farther from the irrigation source. Our results show that for an alfalfa-grass field with sandy loam soil, deep percolation from flood irrigation is a significant source of shallow groundwater recharge.

We attribute the rapid response of shallow groundwater to deep percolation to a relatively shallow water table, to a highly permeable sandy loam soil, and to an aging alfalfa field likely promoting development of macropores. With a much deeper water table, less permeable soil, or frequently tilled field, we might expect to see a muted response to the same irrigation applications. Including the continuum of flow from irrigation application to percolation below the root zone to shallow groundwater response is a valuable approach for understanding irrigation effects on shallow groundwater. Further work that incorporates spatial variability of soil and aquifer hydrological properties into multi-dimensional models will enable characterization of this continuum over large spatial scales.

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