Journal of Hydrology 367 (2009) 138–149

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A root zone modelling approach to estimating groundwater recharge from irrigated areas

J. Jiménez-Martínez [a,b,*], T.H. Skaggs [b], M.Th. van Genuchten [c], L. Candela [a]

[a] Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia, UPC, Gran Capitan s.n., 08034 Barcelona, Spain
[b] US Salinity Laboratory, USDA-ARS, Riverside, CA, USA
[c] Department of Mechanical Engineering, LTTC/COPPE, Federal University of Rio de Janeiro, UFRJ, Rio de Janeiro, Brazil

ARTICLE INFO

Article history:
Received 3 June 2008
Received in revised form 22 December 2008
Accepted 9 January 2009

Associate Editor: Magnus Persson

Keywords:
Root zone
Aquifer recharge
Irrigation
Campo de Cartagena
Water content
Pressure head

SUMMARY

In irrigated semi-arid and arid regions, accurate knowledge of groundwater recharge is important for the sustainable management of scarce water resources. The Campo de Cartagena area of southeast Spain is a semi-arid region where irrigation return flow accounts for a substantial portion of recharge. In this study we estimated irrigation return flow using a root zone modelling approach in which irrigation, evapotranspiration, and soil moisture dynamics for specific crops and irrigation regimes were simulated with the HYDRUS-1D software package. The model was calibrated using field data collected in an experimental plot. Good agreement was achieved between the HYDRUS-1D simulations and field measurements made under melon and lettuce crops. The simulations indicated that water use by the crops was below potential levels despite regular irrigation. The fraction of applied water (irrigation plus precipitation) going to recharge ranged from 22% for a summer melon crop to 68% for a fall lettuce crop. In total, we estimate that irrigation of annual fruits and vegetables produces 26 $hm^3\ y^{-1}$ of groundwater recharge to the top unconfined aquifer. This estimate does not include important irrigated perennial crops in the region, such as artichoke and citrus. Overall, the results suggest a greater amount of irrigation return flow in the Campo de Cartagena region than was previously estimated.

Introduction

Estimating aquifer recharge is important for determining water resource availability and assessing aquifer vulnerability to pollutants (Scanlon et al., 2002). Recharge estimation can be difficult, particularly in arid and semi-arid regions where water tables are typically deep and recharge is predominately focused recharge that emanates from topological depressions such as streams and lakes. The recharge rate is limited by the availability of water at the land surface, which is controlled by temporally and spatially variable climatic factors such as precipitation and evapotranspiration (Scanlon et al., 2002). In some basins the estimation of recharge is additionally complicated by irrigation, which may simultaneously remove water from focused recharge sources while creating new sources of diffuse recharge. In irrigated regions, accurate knowledge of recharge, evaporation, and transpiration is especially important for the sustainable management of scarce water resources (e.g., Gartuza-Payán et al., 1998).

Several methods have been used to estimate groundwater recharge with varying degrees of success (reviews include Gee and Hillel, 1988; Allison et al., 1994; Scanlon et al., 2002; de Vries and Simmers, 2002). The methods can be loosely grouped into three categories depending on whether the focus of the method is surface water, the vadose zone, or the saturated zone. In each of these cases, physical and tracer techniques are possible, as are numerical modelling approaches. The best choice for a particular situation depends upon the spatial and temporal scales being considered and the intended application of the recharge estimate (Scanlon et al., 2002).

In this work, we studied recharge in the Campo de Cartagena area of southeast Spain, a semi-arid region where irrigated agriculture is prevalent. Our objective was to test a root zone modelling approach that can be used to estimate aquifer recharge emanating from irrigated farmland. The modelling approach utilized HYDRUS-1D (Šimůnek et al., 2005), a well-known computer model that simulates water, heat, and solute movement in variably saturated porous media. A critical element of water balance and modelling approaches to recharge estimation is determining *actual* evapotranspiration rates, which can be below *potential* rates for long periods of time in arid and semi-arid regions, even in irrigated systems. Among other general recharge modelling efforts (e.g., Ragab et al., 1997; Finch, 1998; Zhang et al., 1999; Brunner et al., 2004),

* Corresponding author. Address: Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia, UPC, Gran Capitan s.n., 08034 Barcelona, Spain. Tel.: +34 93 401733; fax: +34 93 4017251.
E-mail address: joaquin.jimenez@upc.edu (J. Jiménez-Martínez).

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.01.002

Kendy et al. (2003) evaluated recharge specifically for irrigated cropland using a model in which soil water flow was governed by a tipping-bucket-type mechanism and actual transpiration was computed based on the soil water status using a method introduced by Campbell and Norman (1998). In our work, root zone moisture dynamics are simulated with the Richards equation and root water uptake and transpiration are calculated according to Feddes et al. (1978).

Campo de Cartagena

The Campo de Cartagena plain comprises an area of 1440 km^2 in the Region de Murcia in southeast Spain (Fig. 1). The climate is Mediterranean with an average annual rainfall of 300 mm and a mean annual temperature of 18 °C. Estimates of annual potential evapotranspiration (ET_P) range from 800 to 1200 mm y^{-1}, depending on the estimation method (Sánchez et al., 1989). Tourism is an important industry due to the region's mild climate and many beaches, parks, and golf resorts. However, the dominant industry and land use is agriculture, both irrigated and rainfed. Irrigated farmland comprises an area of approximately 299 km^2, with 128.1 km^2 of annual row crops (principally lettuce and melon), 34.1 km^2 of perennial vegetables (principally artichoke), and 136.8 km^2 of fruit trees (principally citrus). These crops are an important source of fruits and vegetables for the European Union. Drip irrigation is used widely in their production due to the scarcity of water resources and the need for water conservation. Recently, however, drought conditions have worsened, a deterioration that many attribute to climate change. The future of irrigated agriculture in Campo de Cartagena is in doubt; the United Nations Food and Agriculture Organization has identified current water shortage and desertification problems in southeast Spain as possibly being harbingers of what may become a global food crisis (*New York Times*, June 3, 2008).

Geologically, the Campo de Cartagena plain consists of Neogene and Quaternary materials of sedimentary origin (gravel, sand, silt, and clay) overlying the Betic Complex which is comprised of External Zones (sedimentary materials) and Internal Zones (metamorphic materials). The top unconfined aquifer, of Quaternary age, extends over 1135 km^2 with an average thickness of 50 m. Piezometric levels measured in the inner part of the study area are around 20–30 m below the surface, while near the coast they are usually around 1–2 m. Transmissivity values vary widely depending on location and geological material.

A preliminary study by the Spanish Geological Survey (IGME, 1994) estimated that total recharge to the top unconfined aquifer was about 69 hm^3 y^{-1}, 46 hm^3 y^{-1} due to natural recharge and 23 hm^3 y^{-1} due to irrigation return flow (where 1 hm^3 = 10^6 m^3 = 810.71 ac ft). The SGS study used the Thornthwaite method (Thornthwaite, 1948) to estimate natural recharge and, depending on data availability, a combination of methods to estimate irrigation return flows. For regions where crop and irrigation data were available, irrigation return flows were calculated as the difference between the applied water and the potential crop water use. For other areas where only irrigation data were available, irrigation efficiency coefficients for different irrigation methods (e.g., drip, furrow, flooding) were used to determine the fraction of irrigation water going to recharge. Thus the SGS estimate for return flow was based on irrigation water applications only and did not consider water additions due to precipitation. Instead, precipitation-based recharge from irrigated farmland was implicitly included in the SGS estimate of natural recharge, which was a single value calculated for the entire region.

In our work, we calculate irrigation return flows based on combined water inputs from irrigation and precipitation. So that we may better compare our results with those of the SGS, we make the following assumptions and extrapolations about the SGS estimates. According to the land use figures noted above, irrigated farmland covers 26% of the top unconfined aquifer of Campo de Caragena (299 km^2 in an area of 1135 km^2). We therefore assume that 26% of the SGS estimated natural recharge originates from irrigated lands, 0.26×46 hm^3 y^{-1} $\approx$ 12 hm^3 y^{-1}. Thus irrigation return flow accounting for both precipitation and irrigation is 23 hm^3 y^{-1} + 12 hm^3 y^{-1} = 35 hm^3 y^{-1}. We can divide approximately this return flow among annual row crops, perennial vegetables, and fruit trees by partitioning it in proportion to their respective land areas: 15 hm^3 y^{-1} from annual row crops, 4 hm^3 y^{-1} from perennial vegetables, and 16 hm^3 y^{-1} from fruit trees. These totals are only approximate because it is unlikely that the different cropping systems have identical water use efficiencies. Nevertheless, the approximate values are useful for evaluating our results.

Field site and experiment

A study of root zone soil moisture was conducted on an experimental plot at the Tomas Ferro Agricultural Science Center, a research facility operated by the Technical University of Cartagena. The plot was managed according to agricultural practices that are common in the Campo de Cartagena region, including crop rotations (melon and lettuce) and drip irrigation. Meteorological data for the site are available from a Servicio de Información Agraria de Murcia (SIAM, 2007) weather station located 235 m from the experimental plot.

Characterization of the soil properties

An experimental plot measuring 8×3 m^2 was established on a silty loam soil (USDA classification system). To characterize the soil physical properties, two soil cores were extracted from the plot to a depth of 2 m. The cores were sectioned into layers and analyzed in the laboratory to determine soil bulk density (Grossman and Reinsch, 2002), volumetric water content (Topp and Ferré, 2002), and percentages of sand, silt, and clay (Gee and Or, 2002). Soil water retention values at pressure heads greater than −500 cm were measured using a pressure plate extractor (Dane and Hopmans, 2002).

Field experiment

A drip irrigation system, similar to that used in Campo de Cartagena agriculture, was installed on the plot (Fig. 2). The system featured 16 mm inside diameter tubing, 4 L h^{-1} emitters, and an emitter spacing of 30 cm. In total, 36 emitters were installed.

The plot was instrumented to monitor soil water dynamics in the root zone (Fig. 2). Instrumentation consisted of two tensiometers (Soilmoisture Equipment Corp, Goleta, CA, USA) installed vertically at the depths 30, 45, 60, 90 and 120 cm (10 tensiometers total) (Young and Sisson, 2002), and two 44 mm diameter, 2 m deep access tubes for soil moisture measurements with a TRIME-FM TDR probe (Imko GmbH, Ettlingen, Germany) (Laurent et al., 2001, 2005).

Estimation of recharge using root zone modelling

Numerical modelling

We simulated water flow and root water uptake using HYDRUS-1D (Šimůnek et al., 2005). Assuming (i) that the soil is homogeneous and isotropic, (ii) that the air phase does not affect liquid flow processes, and (iii) that water flow due to thermal gradients is negligible, the governing equation for water flow is the 1D Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + 1\right)\right] - S \tag{1}$$

where h = soil water pressure head (L); θ = volumetric water content ($L^3\,L^{-3}$); t = time (T); x = vertical space coordinate (L); K = unsaturated hydraulic conductivity ($L\,T^{-1}$); and S = sink term ($L^3\,L^{-3}\,T^{-1}$), defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake. The sink term is specified in terms of a potential uptake rate and a stress factor (Feddes et al., 1978):

$$S(h) = \alpha(h)S_p \tag{2}$$

where S_p is the potential water uptake rate [$L^3\,L^{-3}\,T^{-1}$] and $\alpha(h)$ is the dimensionless water stress response function ($0 \leqslant \alpha \leqslant 1$) that prescribes the reduction in uptake that occurs due to drought stress. For $\alpha(h)$, we used the functional form introduced by Feddes et al. (1978):

$$\alpha(h) = \begin{cases} \frac{h-h_4}{h_3-h_4}, & h_4 < h \le h_3 \\ 1, & h_3 < h \le h_2 \\ \frac{h-h_1}{h_2-h_1}, & h_2 < h \le h_1 \\ 0, & h \le h_4 \text{ or } h > h_1 \end{cases} \tag{3}$$

where h_1, h_2, h_3, and h_4 are threshold parameters such that uptake is at the potential rate when the pressure head is between h_2 and h_3, drops off linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ or $h > h_1$. Crop-specific values for these parameters (Table 1) were taken from the database contained in HYDRUS-1D (Šimůnek et al., 2005).

The soil hydraulic properties were modelled using the van Genuchten–Mualem constitutive relationships (Mualem, 1976; van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^{1-1/n}} & h < 0 \\ \theta_s & h \ge 0 \end{cases} \tag{4}$$

$$K(h) = K_s S_e^l \{1 - [1 - S_e^{n/(n-1)}]^{1-1/n}\}^2 \tag{5}$$

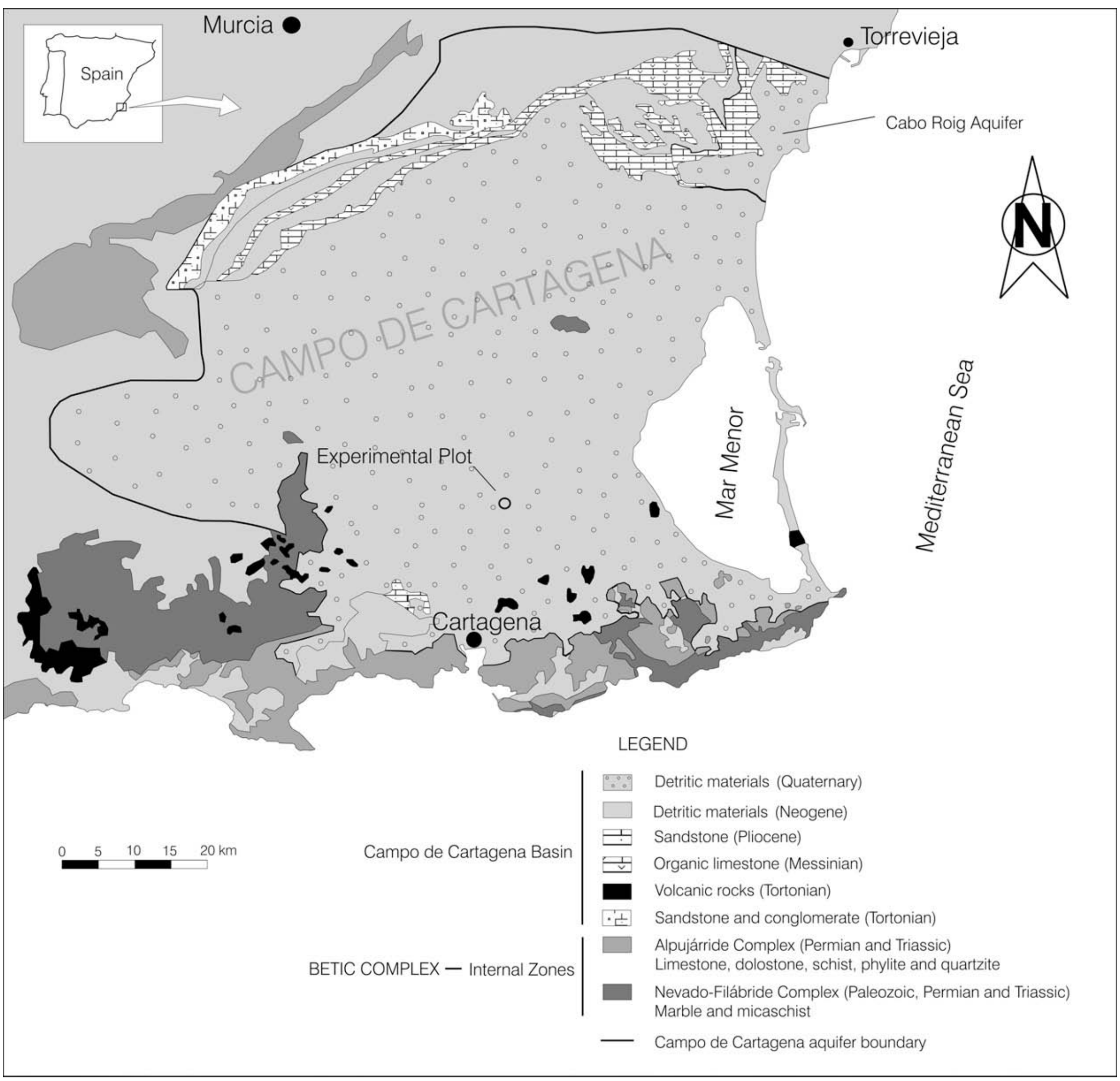

Fig. 1. Location and geology of the Campo de Cartagena area in southeast Spain.

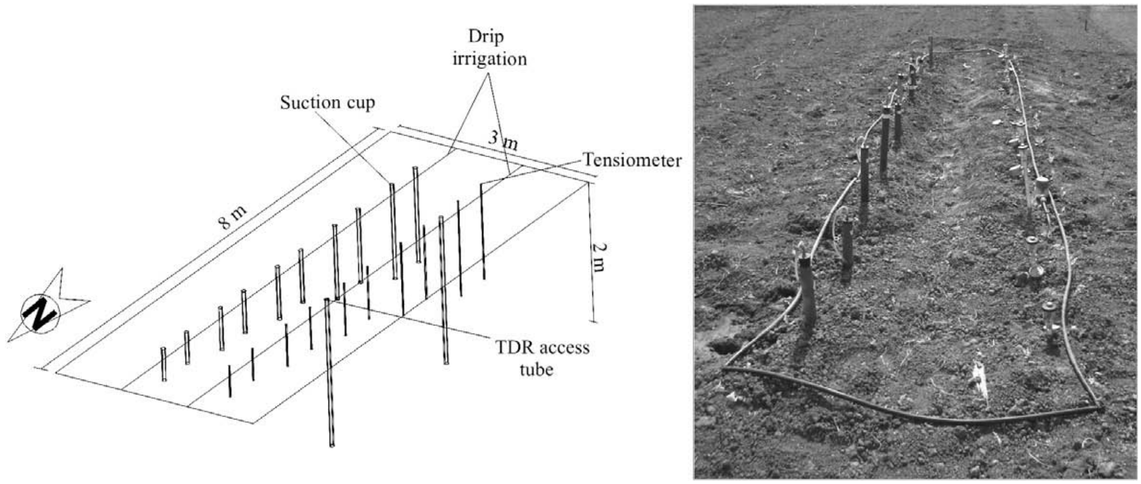

Fig. 2. Photograph and schematic of the experiment plot and the instrumentation.

Table 1
Root water uptake reduction parameters.

Crop	h_1 (cm)	h_2 (cm)	h_3 (cm)	h_4 (cm)
Melon	−10	−25	−400	−8000
Lettuce	−10	−25	−500	−8000

where S_e is effective saturation:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}$$

and where θ_s = saturated water content; θ_r = residual water content; K_s = saturated hydraulic conductivity; α = air entry parameter; n = pore size distribution parameter; and l = pore connectivity parameter. The parameters α, n, and l are empirical coefficients that determine the shape of the hydraulic functions. To reduce the number of free parameters, we took l = 0.5, a common assumption which is based on the work of Mualem (1976).

Running the model required specifying the hydraulic parameters θ_r, θ_s, α, n, K_s, and l. We estimated these parameters using Rosetta (Schaap et al., 2001), a pedotransfer function model that predicts hydraulic parameters from soil texture and related data. Rosetta contains a hierarchy of pedotransfer functions that can be used depending upon available data. We predicted the hydraulic parameters using data for bulk density and percentages of sand, silt, and clay. The data and estimated parameters are given in Table 2. Refinements to these parameter estimates were made subsequently based on model fitting to a subset of the measured water content and pressure head data (details given below).

HYDRUS-1D (Šimůnek et al., 2005) uses the Galerkin finite element method to solve Eqs. (1)–(5). An atmospheric boundary condition (explained in the next section) was implemented at the soil surface while a free drainage condition (unit hydraulic gradient) was used at the bottom, the latter condition being appropriate due to fact that the water table was far below the root zone (Šimůnek et al., 2005).

Potential evapotranspiration and root growth

Implementing the atmospheric boundary condition required specifying daily irrigation and precipitation rates, as well as the potential evaporation and transpiration rates. To determine evaporation and transpiration, we calculated a reference evapotranspiration $ET_0(t)$ using the Penman–Monteith method (e.g., Kashyap and Panda, 2001). The potential evapotranspiration $ET_p(t)$ was then given by (Allen et al., 1998):

$$ET_p(t) = K_c(t) \cdot ET_0(t) \tag{6}$$

where $ET_0(t)$ was discretized in daily time steps and $K_c(t)$ is a crop-specific coefficient that characterizes plant water uptake and evaporation relative to the reference crop. Fig. 3 illustrates the time variation of $K_c(t)$ in terms of annual crop growth stage (the initial, crop development, mid-season, and late season stages). Allen et al. (1998) provide data on the length of the growth stages and the values of K_c for various crops. We used the Allen et al. (1998) method and data to specify for each crop the value of K_c during each growth stage (Table 3, Fig. 3).

With ET_p given by Eq. (6), potential evaporation $E_p(t)$ can be calculated according to (e.g., Kroes and Van Damm, 2003; Pachepsky et al., 2004):

$$E_p(t) = ET_p(t) \cdot \exp^{-\beta \cdot LAI(t)}$$

where β (≈0.4) is the radiation extinction coefficient and $LAI(t)$ is the leaf area index. However, we lacked $LAI(t)$ data so we instead calculated

$$E_p(t) = ET_p f(t) \tag{7}$$

Table 2
Measured soil textural and bulk density data, along with estimated hydraulic parameters.[a]

Depth (cm)	Textural fractions			Bulk density (g cm^{-3})	θ_r (cm cm^{-3})	θ_s (cm cm^{-3})	Log$_{10}$(α) (cm^{-1})	Log$_{10}$(n)	Log$_{10}$(K_s) (cm d^{-1})
	Sand (%)	Silt (%)	Clay (%)						
0–30	18.7	76.0	3.5	1.45	0.04 ± 0.02	0.38 ± 0.06	−2.18 ± 0.51	0.21 ± 0.09	1.67 ± 0.49
30–60	13.8	80.2	6.0	1.52	0.05 ± 0.03	0.38 ± 0.06	−2.16 ± 0.51	0.21 ± 0.09	1.48 ± 0.52
60–90	19.5	77.2	3.3	1.58	0.04 ± 0.03	0.35 ± 0.07	−2.01 ± 0.66	0.19 ± 0.11	1.48 ± 0.67
90–150	10.8	82.0	6.6	1.70	0.04 ± 0.03	0.38 ± 0.08	−2.03 ± 0.76	0.18 ± 0.11	1.12 ± 0.80

[a] Confidence intervals are two standard deviations 95%, estimated by Rosetta.

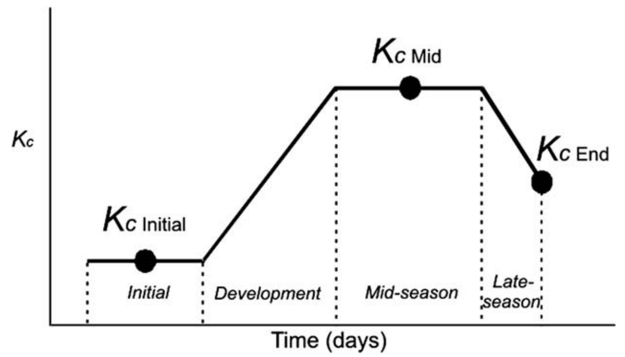

Fig. 3. Illustration of crop growth stages and the time variation of the crop coefficient K_c.

where the function $f(t)$ was specified based on the following reasoning. When a crop is first planted, ground cover is nonexistent, potential evaporation is maximal, transpiration is zero, and thus $f(t) = 1$. Conversely, when the crop reaches the mid-season growth stage, ground cover is complete, evaporation is effectively zero, and thereafter $f(t) = 0$. All that remains is specifying the transition from $f(t) = 1$ at planting to $f(t) = 0$ at the beginning of the mid-season growth stage. Because crop growth typically follows an S-shaped pattern (e.g., Overman and Scholtz, 2002), we modelled this transition using a sigmoid curve.

With the HYDRUS atmospheric boundary condition, water evaporates from the soil surface at the potential rate E_p (a flux boundary condition) as long as the pressure head at the surface remains above a threshold value, h_{crit}. If the soil surface dries out such that the surface pressure head reaches the threshold value, the boundary switches to a constant pressure head condition ($=h_{crit}$), generally leading to a computed actual evaporation rate that is well below the potential rate. In our simulations, h_{crit} was assumed to be $-15\,000$ cm. The results of our simulations were insensitive to this parameter value when specified in the range $-10\,000$ cm to $-15\,000$ cm because the surface soil remained relatively wet due to regular irrigation and thus remained above the h_{crit} threshold.

With ET_p and E_p given by Eqs. (6) and (7), the potential transpiration $T_p(t)$ was specified by:

$$T_p(t) = ET_p(t) - E_p(t) \tag{8}$$

Fig. 4 summarizes the imposed surface boundary condition, showing daily values of precipitation, irrigation, T_p, and E_p.

The modelled rooting depth was assumed to increase with time according to a logistic growth function (Šimůnek et al., 2005), achieving a maximum depth at the end of the crop development stage. Values for the maximum rooting depth for particular crops (Table 3) were derived from Allen et al. (1998).

Results and discussion

Model calibration and predictions

Running HYDRUS-1D using the Rosetta hydraulic parameter estimates resulted in simulations that were in poor agreement with the field data. We therefore attempted to calibrate the soil hydraulic property model Eqs. (4) and (5) using a subset of the data. The most intensive data collection at the site occurred during the cultivation of melon from 17 May to 10 September, 2007, comprising day of year (DOY) 137-253. We used this data set and the parameter optimization routines of HYDRUS-1D to calibrate the soil hydraulic parameters. Several possible parameterizations were considered which differed according to the number of soil layers (from 1 to 4) and the number and type of hydraulic parameters that were fitted for each layer (different combinations of 1–4 parameters among α, n, K_s, and θ_s). The initial estimates for the parameters when fitted, or their fixed value when not fitted, were the Rosetta estimates given in Table 2. If the results of the optimization looked promising, the fitting was repeated using different initial estimates to ensure that the same optimized parameter values were obtained. The best overall parameterization was determined informally based on diagnostic information provided by the HYDRUS-1D routines about the model fit and the convergence behaviour of the inverse algorithm, visual inspection of the model fit to the data (including laboratory water retention data), and the principle of parsimony (i.e., if two parameterizations produced a roughly equal fit to the data, we took the simpler of the two, where "simpler" means fewer fitted parameters and/or soil layers). The best parameterization was found to involve four soil layers with two adjustable parameters, α and n, for each layer. The final fitted hydraulic parameter values are given in Table 4; the other parameter values are those estimated with Rosetta (Table 2). Fitting more than two parameters per layer tended to cause the inverse algorithm to fail. Four soil layers produced a better fit to the data than was possible with fewer layers in the profile. Overall, the numerical solution with four layers and α and n fitted for each layer provided the best correlation between measured and simulated water content and pressure head values. Fig. 5 shows the water content and pressure head data for various depths in the soil profile, along with the corresponding fitted model simulation. Table 5 gives goodness-of-fit measures for the calibrated simulation run and data, including $R^2 = 0.90$ for the combined water content and pressure head data. Correlation coefficients $r_{x,y}$ computed by HYDRUS-1D for the eight fitted parameters were $|r_{x,y}| < 0.4$, with three exceptions: $r_{\alpha_1,\alpha_2} = -0.54$, $r_{\alpha_1,\alpha_4} = -0.55$, and $r_{\alpha_3,n_3} = -0.75$ (where numerical subscripts on α and n indicate the soil layer).

With the fitted parameterization, HYDRUS-1D was next used to predict the root zone soil moisture dynamics during the growing periods of two lettuce crops at the site, the first one grown between 7 February and 16 May 2007 (DOY 38-136) and the second one between 25 September and 24 December 2007 (DOY

Table 3
Growth and evapotranspiration coefficients for various crops (source: Allen et al., 1998).

Crop	Plant date	Growth stage (number of days)				Crop coefficient (K_c)			Maximum root depth (cm)
		Initial	Development	Mid-season	Late-season	Initial	Mid	End	
Lettuce	January/September	35/30	50/40	45/25	10/10	0.7	1	0.95	30–50
Broccoli	January/September	35	45	40	15	0.7	1.05	0.95	45–60
Cauliflower	January/September	35	50	40	15	0.7	1.05	0.95	45–60
Celery	January/September	25	40	45	15	0.7	1.05	1	45–60
Endive	January/September	[a]	[a]	[a]	[a]	0.7	0.95	0.90	30–45
Melon	May	25	35	40	20	0.5	1.05	0.75	80–150
Watermelon	May	20	30	30	30	0.4	1	0.75	80–200

[a] No data available, but casual observation suggests growth stages similar to those of lettuce.

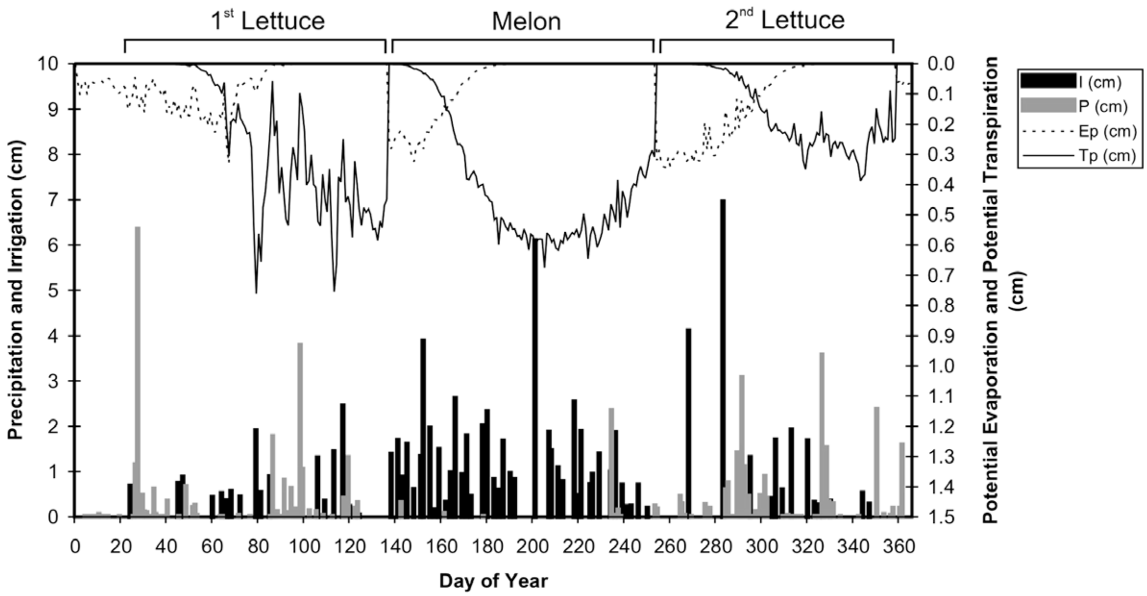

Fig. 4. Summary of the modelled soil surface boundary conditions (I = irrigation; P = precipitation; E_p = potential evaporation; T_p = potential transpiration).

Table 4
Fitted hydraulic parameter values with 95% confidence intervals.

Depth (cm)	α (cm^{-1})	n (–)
0–30	0.078 ± 0.01	1.16 ± 0.01
30–60	0.046 ± 0.005	1.23 ± 0.02
60–90	0.014 ± 0.004	1.27 ± 0.07
90–150	0.020 ± 0.002	1.46 ± 0.05

268-358). Figs. 6 and 7 compare the predictions with the experimental data at various depths in the soil profile. Overall, good agreement was achieved between the field measurements and the HYDRUS-1D predictions. The correlation (R^2) between measured and predicted water contents and pressure heads was 0.82 for both of the lettuce crops. Additional measures of goodness-of-fit are given in Table 5.

Recharge estimation

We next used the calibrated model simulations to evaluate the root zone soil water balance and calculate the annual recharge rate. The components of the water balance were water additions due to irrigation (I) and precipitation (P), losses due to evapotranspiration and drainage below the root zone, and changes in root zone water storage. Drainage from the bottom of the soil profile was assumed to be irrigation return flow, equal to the groundwater recharge rate. Based on the simulated drainage, we could determine the recharge rate generated during cultivation of different crops at different times of the year. Fig. 8 shows the cumulative drainage (recharge) as a function of time computed for the three cropping periods. The percentages of applied water ($P + I$) becoming recharge were 24.6% for the first lettuce crop (DOY 20-136), 21.7% for the melon crop (DOY 137-253), and 68.2% for the second lettuce crop (DOY 254-358). The higher percentage during the last period was due to higher precipitation and lower transpiration rates (Fig. 4). In total, recharge during the period DOY 20-358 was 492 mm.

Fig. 8 also shows for the three cropping periods the cumulative potential and actual transpiration rates. Actual transpiration was frequently lower than the potential rate because soil moisture at various times was insufficient to sustain the potential uptake rate, with uptake being reduced according to Eq. (2). This aspect of the root zone modelling methodology (i.e., the physically based calculation of the onset of water stress and subsequent reduced uptake) is crucial for calculating recharge in arid and semi-arid regions where ET may drop below potential rates, even in irrigated systems.

Vegetables, fruits, and citrus are the principal crops in the Campo de Cartagena area. In addition to the melon and lettuce crops grown in our study, common fruits and vegetables include broccoli, cauliflower, celery, endive, and water melon. As shown in Table 3, these crops have similar cultivation periods and water requirements as the crops grown in our field plot, and they are grown with the same climate and soil conditions, which are relatively uniform across the Campo de Cartagena region (Ramírez et al., 1999). Therefore, as a first approximation, we assumed our results for melon and lettuce to be representative of irrigation return flows for seasonal fruits and vegetables in the Campo de Cartagena plain. This approach allowed us to use statistics for crop acreages in the Campo de Cartagena area (CARM, 2007) to estimate recharge to the top unconfined aquifer from irrigated annual fruit and vegetable croplands. Row crops in the region cover about 128.1 km^2. Approximately 19.3% of the crops are cultivated between January and April (lettuce, broccoli, cauliflower, celery, and endive), 25.3% are cultivated between May and August (sweet melon and water melon), while 55.4% are cultivated between September and December (lettuce, broccoli, cauliflower, celery, and endive). Using our recharge values for each of these periods, we estimate that recharge to the top unconfined aquifer from irrigation of annual row crops during 2007 was 26 hm^3. This value does not include recharge arising from important irrigated perennial crops such as artichoke and citrus.

Notably, our recharge value of 26 hm^3 y^{-1} for annual row crops is almost two times greater than the 15 hm^3 y^{-1} estimate that was derived above using data from the Spanish Geological Survey (IGME, 1994). Although the SGS estimate encompassed different estimation methods depending upon available data for the various crops and cultivated areas, the value was based in part on calculations which assumed crop water use was at the potential rate. As indicated by Fig. 8, that assumption tends to overestimate water use and hence underestimates recharge. Based on these considerations and our calculation of 26 hm^3 y^{-1}

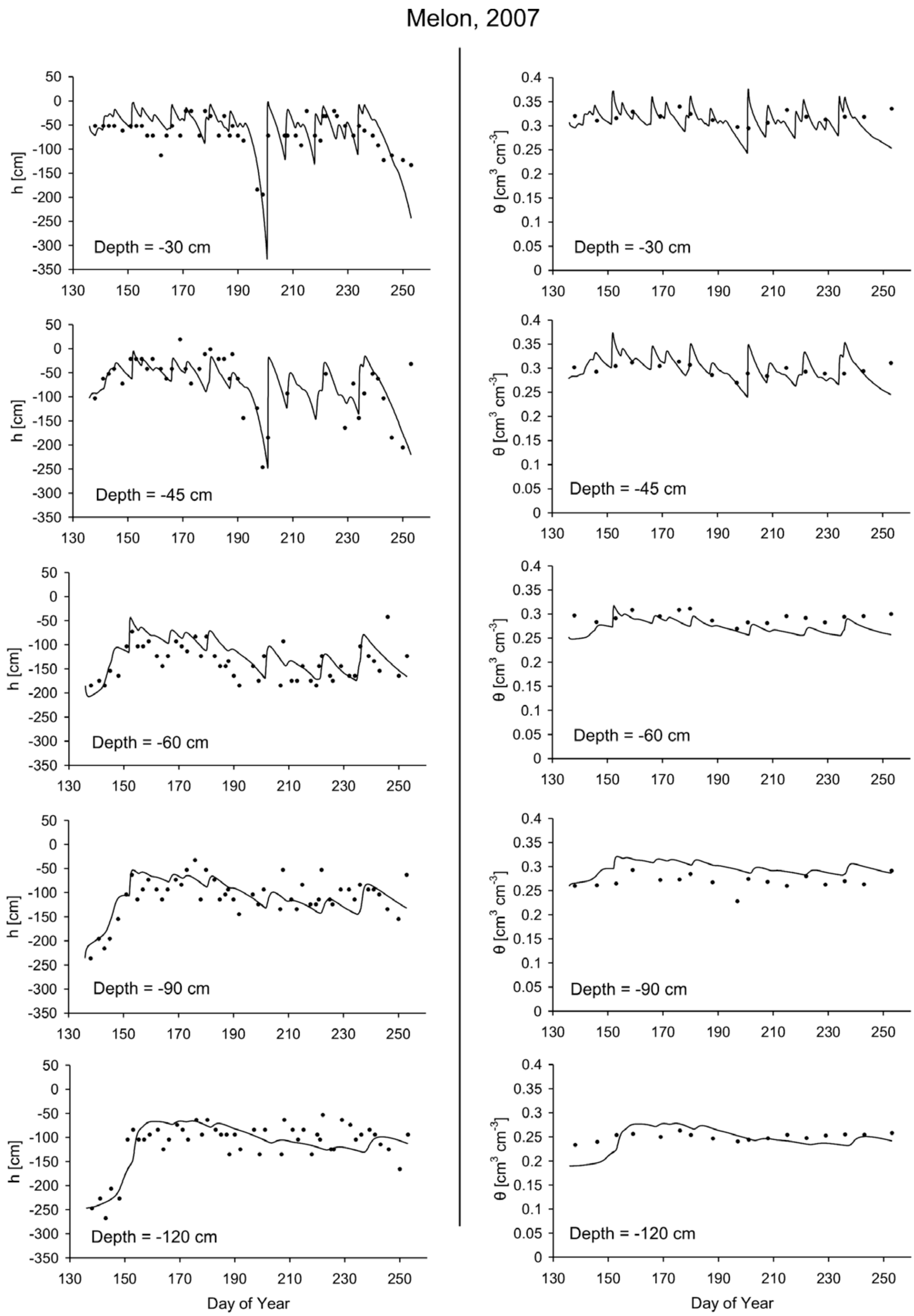

Fig. 5. Pressure head and water content data (points) measured at various depths in the soil profile, along with final fitted HYDRUS simulations (solid lines) for melon.

for annual fruits and vegetables, we believe that that recharge from irrigated farmland to the top unconfined aquifer of the Campo de Cartagena region is likely to be larger than previously estimated.

Uncertainty and sensitivity assessment

Our modelling approach contains several potential sources of uncertainty or error. We can distinguish between two levels or

Table 5
Goodness-of-fit measures for simulations and experimental data.

Simulation	Data set	*RMSE*[a]	*MAE*[b]	R^2
Melon (DOY 137-253) (calibration)	Water content (θ)	0.029	0.024	
	Pressure head (h)	33.776	27.971	
	Combined θ and h			0.90
1st Lettuce (DOY 38-136) (prediction)	Water content (θ)	0.024	0.022	
	Pressure head (h)	56.630	41.271	
	Combined θ and h			0.82
2nd Lettuce (DOY 268-358) (prediction)	Water content (θ)	0.023	0.019	
	Pressure head (h)	40.013	31.279	
	Combined θ and h			0.82

[a] Root mean square error, $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$.
[b] Mean absolute error, $MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i|$.

types of uncertainty. On one hand, uncertainty exists about the computed root zone drainage at our plot or field. In this context, sources of uncertainty include the values of various model parameters such as the soil hydraulic parameters in Eqs. (4) and (5), the daily reference evapotranspiration rate $ET_0(t)$, crop coefficients $K_c(t)$, and drought stress parameters (e.g., h_3 in Eq. (3), the threshold pressure head below which uptake is reduced). Quantifying the effect of these parameter uncertainties on drainage calculations requires knowledge of their statistical variability and correlation structure. In the case of the hydraulic parameters α and n, we have information in the form of 95% confidence intervals and correlation coefficients computed by HYDRUS-1D as part of the parameter optimization (Table 4). For other hydraulic parameters, estimated confidence intervals are available from the Rosetta model (Table 2), but those estimates are unrealistically broad because they are based on only the soil separate and bulk density data and have not been conditioned on the water content and pressure head field data. To our knowledge, the literature provides little or no information on quantifying uncertainty in other model parameters such as crop coefficients.

A second type or source of uncertainty involves extrapolation of the field results to the larger region. Here, sources of uncertainty include the data on regional irrigation practices, cropping rotations and acreages, and so forth—the type of uncertainty that exists in any modelling or water balance estimation of recharge. Additionally, we may consider how specific model parameters vary in the region and how those variations would affect root zone drainage calculations. Again, however, little knowledge exists on how to quantify such variability in parameters like ET_0 or $K_c(t)$. For the hydraulic parameters, the Rosetta uncertainty estimates (Table 2) potentially provide a good starting point for quantifying the effects of hydraulic property uncertainty. Those estimates could, for example, serve as the basis for a Monte Carlo calculation of uncertainty in the recharge estimate. However, such a calculation is more complicated than it may first appear. The Rosetta uncertainty estimates are quite broad. For example, the bounds for the 95% confidence intervals for K_s span an order-of-magnitude. With that kind of variability, a problem that may be encountered is that a given irrigation regime may not be sensible over the whole range of soil properties: a realistic regime for a medium conductivity soil may result in water logging in a low conductivity soil (a specific example is given in the sensitivity calculations discussed below). Thus, a quantitative analysis of hydraulic property uncertainty would have to somehow account for the relationship between soil properties and irrigation regimes (i.e., surface boundary conditions).

In sum, it does not seem possible at this time to put quantitative confidence intervals on our recharge estimate owing to a lack of knowledge about parameter variability and correlation structure at multiple levels. However, it is possible to get some sense of the importance of parameter uncertainty by performing a sensitivity analysis. For this analysis, we performed a series of simulations in which individual parameters, or in one case a set of parameters, were perturbed a fixed amount while all other parameters were held at their baseline values (that is, the values used in our recharge calculations). The effect of the various parameter perturbations on the calculated recharge was then evaluated. Parameters considered for sensitivity analyses were α, n, K_s, θ_s, θ_r, l, $K_c(t)$, h_3, and $ET_0(t)$. Note in the following that Rosetta assumes α, n, and K_s are lognormally distributed, such that the confidence intervals are not symmetric about the (geometric) mean parameter estimate after antilog transformation. Also note that in our calibration procedure above we did not treat the hydraulic parameter l as adjustable, instead fixing its value at $l = 0.5$; we include it in our sensitivity analysis for completeness and because Rosetta generally estimates high levels of uncertainty for this parameter.

The first set of sensitivity calculations involved perturbing the hydraulic parameters α, n, K_s, θ_s, θ_r, and l one at a time in individual soil layers. The perturbations to the parameter values in this case were large, equal to the bounds of the 95% confidence intervals given in Table 2. The results for these calculations showed that among the parameters considered, recharge calculations were least sensitive to the water contents θ_s and θ_r. Setting either of these parameter values to the bounds of the 95% confidence intervals in any of the four soil layers resulted in a change to the computed recharge of less than 3%, a small change considering that the 95% confidence bounds corresponded to parameter perturbations of about ±15% to ±23% for θ_s (depending on the soil layer), and ±54% to ±70% for θ_r (Table 2). Relatively low sensitivity was also found for the remaining soil hydraulic parameters (α, n, K_s, l) in the middle two soil layers. Setting K_s or l in those layers to the 95% confidence bounds resulted in changes to the computed recharge of less than 3%, while equivalent perturbations to α or n produced changes less than 5%. Again, the changes in computed recharge were fairly small considering the size of the parameter perturbations, which were about ±25% for n, between −70% and +400% for K_s and α (recall the asymmetric confidence intervals), and greater than 1000% for l. Higher sensitivity was found for α, n, K_s, and l in the surface soil layer. Perturbations to those parameters resulted in changes to the computed recharge that ranged from 3% to 12% with one notable exception: the lower bound for the surface saturated conductivity resulted in an increase of 42% to the calculated recharge. The reason for this large increase was that the low surface conductivity caused the surface soil to stay very close to saturation for long periods of time, such that uptake was reduced according to Eq. (3) and hence simulated drainage increased (the Feddes et al. (1978) model, Eq. (3), specifies that uptake reduction occurs both when the soil is excessively wet and when it is too dry). The highest sensitivity to hydraulic parameters was found in the bottom soil layer where the retention and conductivity functions directly impact the drainage

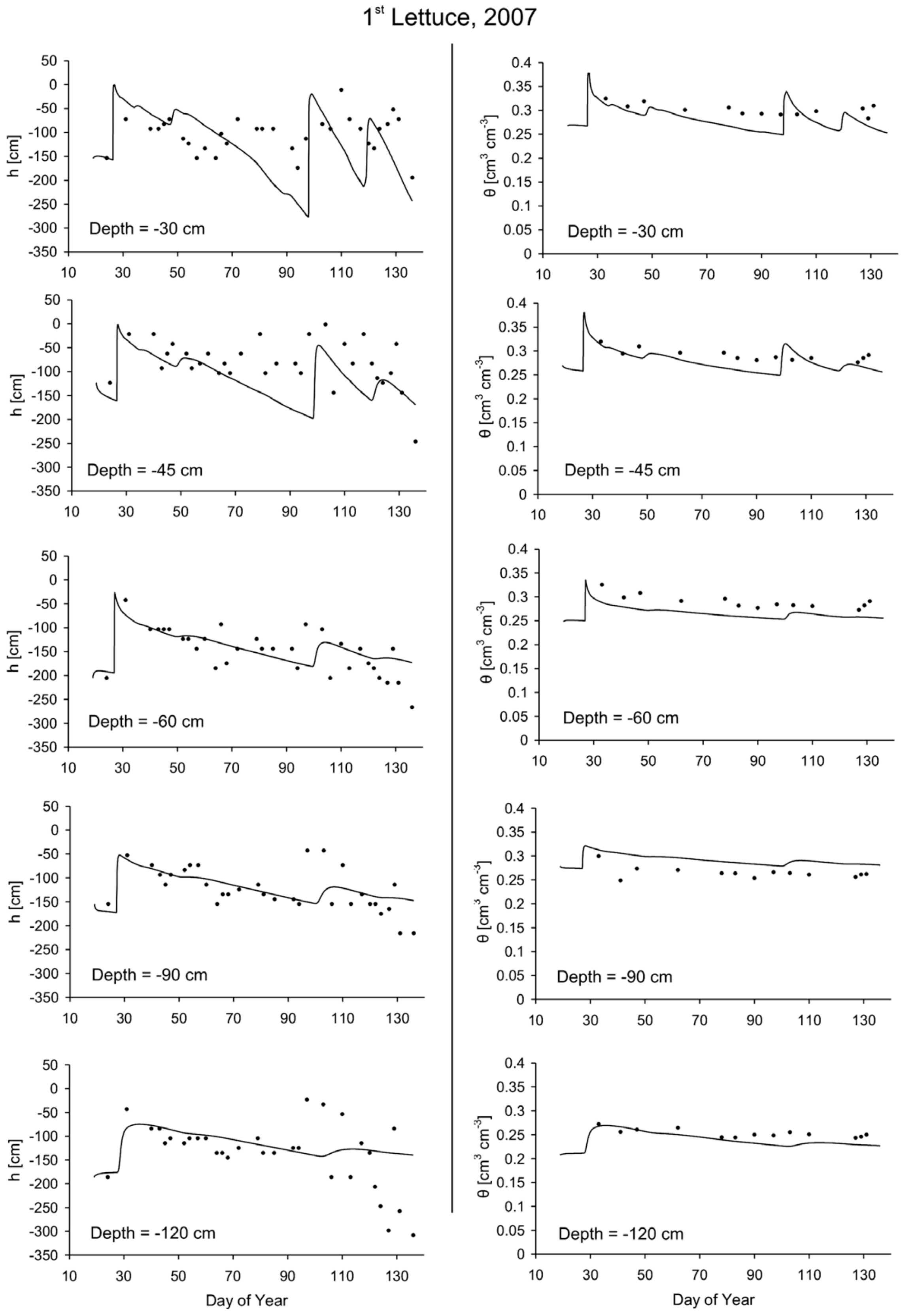

Fig. 6. Pressure head and water content data (points) measured at various depths in the soil profile, along with HYDRUS predictions (solid lines) for the first lettuce crop.

of water out of the root zone. In this layer, setting individual parameters to the lower and upper bounds of the 95% confidence region led to changes in recharge of, respectively, −21% and +18% for K_s, −6% and −1% for n, +13% and −5% for l, and +46% and −23% for α. Although some of those changes are quite substantial, keep in mind the very large perturbations (e.g., the bounds for α corresponded to perturbations of about −80% and +475%) and the low likelihood of such a soil parameter value.

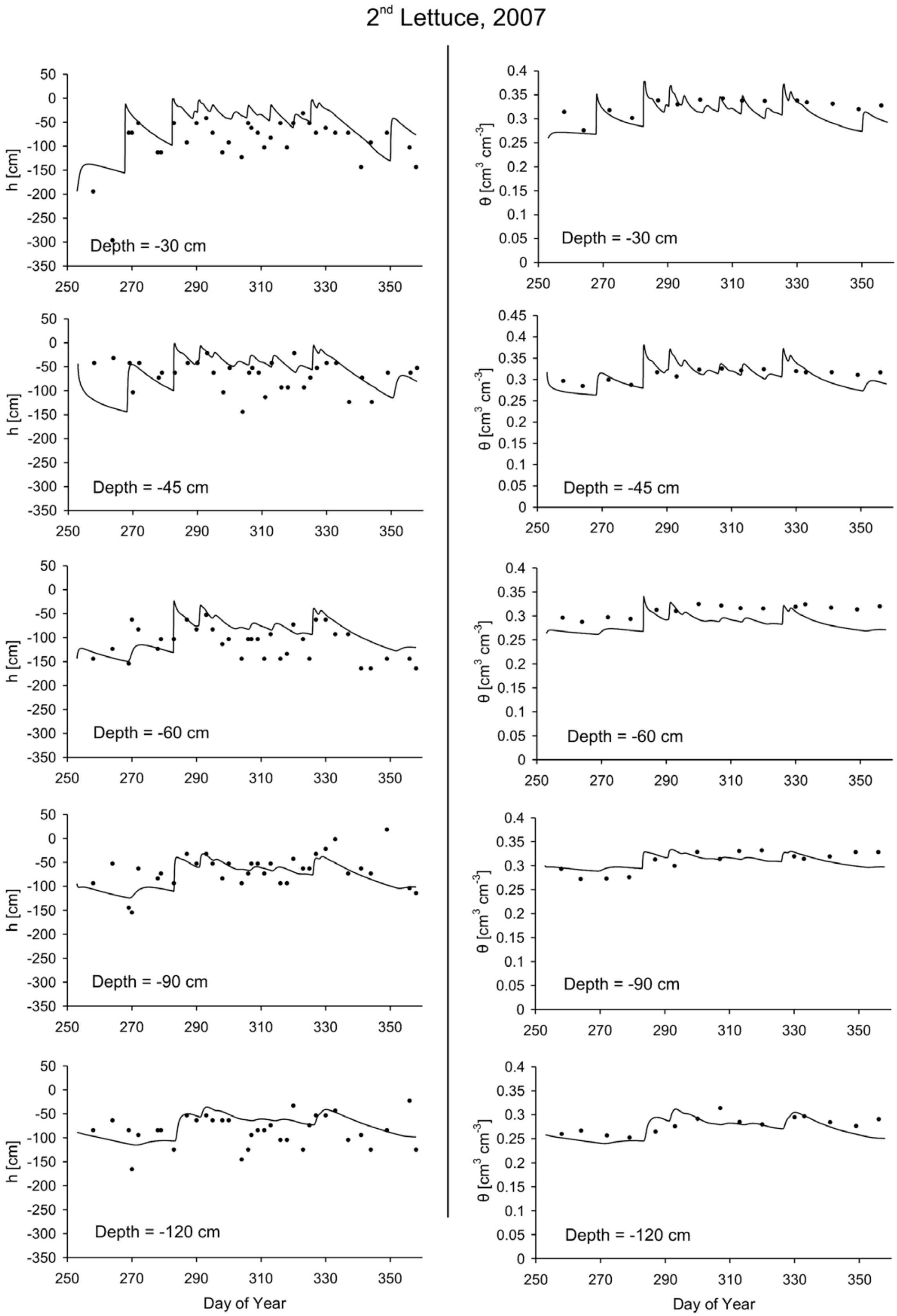

Fig. 7. Pressure head and water content data (points) measured at various depths in the soil profile, along with HYDRUS predictions (solid lines) for the second lettuce crop.

When narrower, more realistic bounds for α and n in individual soil layers were evaluated (Table 4), the changes in the calculated recharge were ±3% or less. Unlike the bounds discussed in the previous paragraph, these confidence intervals incorporated our measured water content and pressure head data, and thus are likely to be more reflective of the uncertainty that existed at our experi-

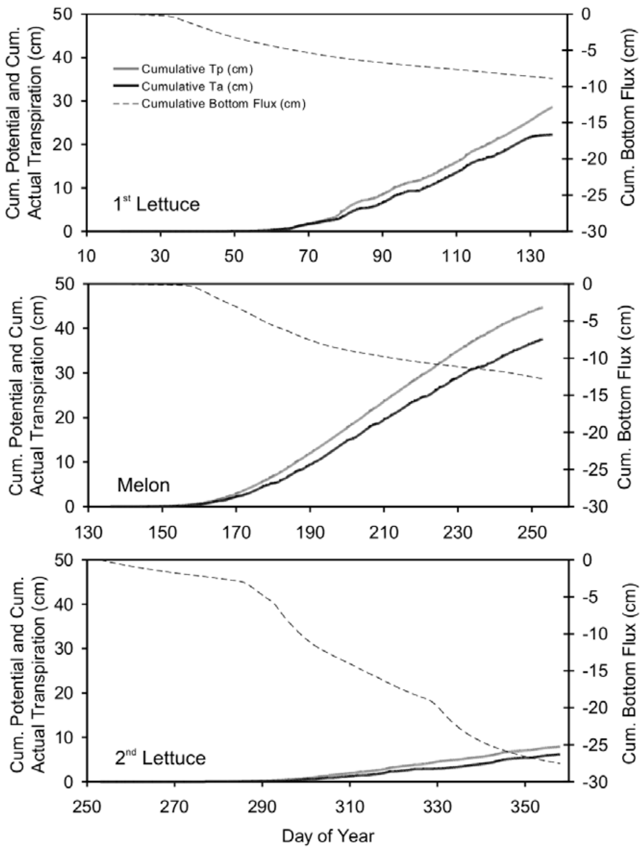

Fig. 8. Cumulative potential transpiration, actual transpiration, and drainage (recharge) rates computed for the three crops.

mental site. We additionally considered smaller, ±10% perturbations to the remaining hydraulic parameters (K_s, θ_s, θ_r, and l) in individual soil layers. In these calculations, the calculated recharge was least sensitive to θ_r (∼1% change in recharge), while the other parameter perturbations altered recharge by between 7% and 15%. The simulation for a −10% perturbation of n was not completed because the small n value caused numerical difficulties in the simulation model (a well-known problem for $n \to 1$). Lastly, we considered simultaneously perturbing the same hydraulic parameter in all soil layers. Using ±10% perturbations, computed recharge was again insensitive to θ_r (about 1% change in recharge), whereas changes in recharge for other parameters were about 7–15%. The lower bound calculation for n was again aborted due to numerical problems.

The final sensitivity calculations involved ±10% perturbations to the parameters h_3 and $K_c(t)$. Note that because $K_c(t)$ and $ET_0(t)$ appear as a product in Eq. (6), results for a ±10% perturbation in $K_c(t)$ are identical to results that would be obtained for a ±10% perturbation in $ET_0(t)$. The recharge calculation was relatively insensitive to perturbations of h_3, with the calculated recharge changing by less than 1%. Greater sensitivity was found for $K_c(t)$ or $ET_0(t)$, where the 10% perturbations altered the recharge calculation by about 6–7%.

In sum, an accurate characterization of prediction uncertainty is problematic because of a lack of knowledge about the underlying parameter variability and parameter correlation structure. Our conclusion that irrigation return flow in the Campo de Cartagena region is likely larger than previously estimated is based on our calculated value of 26 $hm^3\,y^{-1}$ recharge from annual row crops and a previous estimate of 15 $hm^3\,y^{-1}$. In our view, that conclusion would remain valid unless our estimate was about 25% too large, in which case the two recharge estimates would not be that different considering the various approximations and assumptions underlying both numbers. The results of our sensitivity analysis do not rule out the possibility of that level of uncertainty in our calculations, but they do suggest it is unlikely. Future work aimed at quantifying uncertainty in parameters such as $K_c(t)$ or $ET_0(t)$ would greatly benefit efforts to determine uncertainty in recharge calculations.

Summary and conclusions

In irrigated semi-arid and arid regions, accurate knowledge of groundwater recharge is important for the sustainable management of scarce water resources. The Campo de Cartagena plain in southeast Spain is a semi-arid region where irrigation return flow accounts for a substantial portion of recharge. In this study we estimated irrigation return flow using a root zone modelling approach in which irrigation, evapotranspiration, and soil moisture dynamics for specific crops and irrigation regimes were simulated with HYDRUS-1D. The model was calibrated using field data collected at an experimental plot in the area. Good agreement was achieved between the HYDRUS-1D simulations and field measurements made under melon and lettuce crops. The simulations showed that water use by the crops was below potential levels, despite regular irrigation.

Assuming that the HYDRUS-1D results for melon and lettuce were representative of similar crops grown in the Campo de Cartagena, we estimated that the cultivation of annual fruits and vegetables on irrigated farmland produces 26 $hm^3\,y^{-1}$ groundwater recharge to the top unconfined aquifer. This estimate does not include important irrigated perennial crops in the region such as artichoke and citrus. Overall, the results point toward a greater amount of irrigation return flow in the Campo de Cartagena region than was estimated previously by the Spanish Geological Survey. Our calculations indicated a high level of recharge late in the year when potential evapotranspiration was lower. Improved irrigation scheduling based on soil moisture status and crop water requirements could significantly reduce irrigation return flows.

More generally, our root zone modelling approach shows promise as a method for estimating recharge in irrigated semi-arid regions. Compared with other techniques, the modelling approach is relatively data intensive, involving several of crop- and soil-specific parameters. However, often times these parameters can be approximated using existing databases and estimation tools. For example, maps of soil texture and related soil physical properties are available for many locations; soil hydraulic parameters can be easily estimated from those data using pedotransfer functions or related approaches. Likewise, water stress parameters for many important crops have been tabulated (e.g., Kroes and van Damm, 2003). Perhaps more difficult will be specifying representative irrigation practices, which may or may not be uniform across a region. Future work aimed at quantifying parameter uncertainty and correlation structure is needed to establish confidence intervals for model predictions.

Acknowledgements

This work has been developed within Projects CGL-2004-05963-C04-01 and CGL2007-66861-C04-03, national plan I+D+I Spanish Ministry of Education. Gratitude is expressed to Almudena Jiménez for collecting data and working with the instrumentation, and to the Technical University of Cartagena.

References

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

Allison, G.B., Gee, G.W., Tyler, S.W., 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. Soil Sci. Soc. Am. J. 58, 6–14.

Brunner, P., Bauer, P., Eugster, M., Kinzelbach, W., 2004. Using remote sensing to regionalize local precipitation recharge rates obtained from the chloride method. J. Hydrol. 294 (4), 241–250.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics, second ed. Springer-Verlag, New York.

CARM, 2007. Consejería de Agricultura y Agua de la Región de Murcia. Agrarian Statistics Data. <http://www.carm.es>.

Dane, J.H., Hopmans, J.W., 2002. Pressure plate extractor. In: Dane, J., Topp, C. (Eds.), Methods of Soil Analysis, Part 4, SSSA Book Series, vol. 5. Am. Soc. Agron., Madison, WI, pp. 688–690.

de Vries, J.J., Simmers, I., 2002. Groundwater recharge: an overview of processes and challenges. Hydrogeol. J. 10, 5–17.

Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. Simulation of Field Water Use and Crop Yield. John Wiley and Sons, NY.

Finch, J., 1998. Estimating direct groundwater recharge using a simple water balance model – sensitivity to land surface parameters. J. Hydrol. 211, 112–125.

Gartuza-Payán, J., Shuttleworth, W.J., Encinas, D., McNeil, D.D., Stewart, J.B., DeBruin, H., Watts, C., 1998. Measurement and modelling evaporation for irrigated crops in northwest Mexico. Hydrol. Process. 12, 1397–1418.

Gee, G.W., Hillel, D., 1988. Groundwater recharge in arid regions: review and critique of estimation methods. Hydrol. Process. 2, 255–266.

Gee, G.W., Or, D., 2002. Particle size analysis. In: Dane, J., Topp, C. (Eds.), Methods of Soil Analysis, Part 4, SSSA Book Series, vol. 5. Am. Soc. Agron., Madison, WI, pp. 255–294.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J., Topp, C. (Eds.), Methods of Soil Analysis, Part 4, SSSA Book Series, vol. 5. Am. Soc. Agron., Madison, WI, pp. 201–228.

IGME, 1994. Las aguas subterráneas del Campo de Cartagena (Murcia). Spanish Geological Survey, Spain. 62 pp.

Kashyap, P.S., Panda, R.K., 2001. Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. Agric. Water Manage. 50, 9–25.

Kendy, E., Gérard-Marchant, P., Walter, M.T., Zhang, Y., Liu, C., Steenhuis, T.S., 2003. A soil–water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. Hydrol. Process. 17, 2011–2031.

Kroes, J.G., Van Damm, J.C., 2003. Reference Manual SWAP: Version 3.0.3. Rep. 773. Alterra Green World Res., Wageningen, The Netherlands.

Laurent, J.P., Ruelle, P., Delage, L., Bréda, N., Chanzy, A., Chevallier, C., 2001. On the use of the TDR trime-tube system for profiling water content in soil. In: Proceedings TDR'01, Evanston-Illinois, USA, 5–2 September 2001, pp. 1–10.

Laurent, J.P., Ruelle, P., Delage, L., Zaïri, A., Ben Nouna, B., Adjmi, T., 2005. Monitoring soil water content profiles with a commercial TDR system: comparative field tests and laboratory calibration. Vadose Zone J. 4, 1030–1036.

Mualem, Y., 1976. A new model predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522.

Overman, A.R., Scholtz, R.V., 2002. Mathematical Models of Crop Growth and Yield. Marcel Dekker, Inc., New York.

Pachepsky, Y.A., Smettem, K.R.J., Vanderborght, J., Herbst, M., Vereecken, H., Wosten, J.H.M., 2004. Reality and fiction of models and data in soil hydrology. In: Feddes, R.A. et al. (Eds.), Unsaturated-Zone Modeling. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Ragab, R., Finch, J., Harding, R., 1997. Estimation of groundwater recharge to chalk and sandstone aquifers using simple soil models. J. Hydrol. 190, 19–41.

Ramírez, I., Vicente, M., García, J., Vaquero, A., 1999. Mapa digital de suelos de la Región de Murcia. Consejería de Agricultura, Agua y Medio Ambiente. Handbook and CD-ROM, p. 78.

Sánchez, M.I., López, F., Del Amor, F., Torrecillas, A., 1989. La evaporación y evapotranspiración en el Campo de Cartagena y Vega Media del Segura. Primeros resultados. Anales Edafología Agrobiol, 1239–1251.

Scanlon, B.R., Healy, R.W., Cook, P.G., 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10, 18–39.

Schaap, M.G., Leij, F.J., van Genuchten, M.Th., 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163–176.

SIAM, 2007. Servicio de Información Agraria de Murcia. Climatology Data. <http://www.siam.imida.es>.

Šimůnek, J., van Genuchten, M.Th., Šejna, M., 2005. The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variability Saturated Media, Version 3.0. Department of Environmental Sciences University of California Riverside, Riverside, California, USA, 270 pp.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55–94.

Topp, G.C., Ferré, P.A., 2002. Thermogravimetric method using convective oven-drying. In: Dane, J., Topp, C. (Eds.), Methods of Soil Analysis, Part 4, SSSA Book Series, vol. 5. Am. Soc. Agron., Madison, WI, pp. 422–424.

van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Young, M.H., Sisson, J.Y., 2002. Tensiometry. In: Dane, J., Topp, C. (Eds.), Methods of Soil Analysis, Part 4, SSSA Book Series, vol. 5. Am. Soc. Agron., Madison, WI, pp. 575–609.

Zhang, L., Dawes, W.R., Hatton, T.J., Reece, P.H., Beale, G.T., Packer, I., 1999. Estimation of soil moisture and groundwater recharge using the TOPOG_IRM model. Water Resour. Res. 35, 149–161.