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

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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),

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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, $0.26 \times 46\ hm^3\ y^{-1} \approx 12\ hm^3\ y^{-1}$. 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 $8 \times 3\ m^2$ 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