Journal of Hydrology 522 (2015) 618–627

Contents lists available at ScienceDirect

Journal of Hydrology

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

Examination of groundwater recharge with a calibrated/validated flow model of the deep vadose zone

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ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form 8 January 2015
Accepted 10 January 2015
Available online 20 January 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Rao S. Govindaraju, Associate Editor

Keywords:
Deep percolation
Vadose zone
Flow and transport model
Groundwater recharge

SUMMARY

Recharge estimations are required for efficient groundwater systems management. Better estimations could be obtained by improving our understanding of the relationship between climate factors and recharge. This study explores the calibration of a Richards' equation-based model to transient deep vadose zone data, thereby allowing simulation of groundwater recharge over long periods and an investigation of the temporal correlations between recharge and precipitation. An array of four vadose zone-monitoring systems implemented in four different slanted boreholes drilled in different orientations into a deep vadose zone sandy formation (20 m × 20 m × 20 m) enabled continuous monitoring of water content at selected depths and locations across the entire vadose zone under a Mediterranean climate. This unique high-resolution set of transient deep vadose zone data was used for inverse simulations. The flow model was then validated with a set of data under different atmospheric boundary conditions. The long-term mean annual recharge under a natural sand dune was calculated as 327 mm year^{-1}, 72% of the average annual precipitation (1996/7–2012/3), reflecting low evapotranspiration and runoff. The temporal cross-correlation analysis showed high correlations between the accumulated precipitation (over 6–9 months) and the monthly recharge after 3 to 4 months. Therefore, we conclude that the recharge fluxes are mainly influenced by the relatively recent (5–12-months) precipitation patterns. Including this time lag between precipitation and recharge, a predictive regression model was developed in which the May-to-April recharge is explained by annual precipitation in the previous year.

1. Introduction

Recharge estimations play an important role in groundwater systems management and research. The magnitude and timing of groundwater recharge are controlled by climatic and geological factors and have long been of scientific and practical interest (Ng et al., 2009; Smerdon et al., 2010; Kim and Jackson, 2012). Empirical relationships and statistical measures have been used to assess the influence of these factors on recharge (Wu et al., 1996; Kennett-Smith et al., 1994; Jan et al., 2007; Lorenz and Delin, 2007; Sheffer et al., 2010; Kim and Jackson, 2012; Wohling et al., 2012).

Unsaturated flow modeling, in which the Richards' equation is solved numerically, has been used for estimations of groundwater recharge under various conditions (Wang et al., 2009; Nolan et al., 2010; Kurtzman and Scanlon, 2011; Botros et al., 2012; Kim and Jackson, 2012; Turkeltaub et al., 2014). Solutions of the Richards' equation require knowledge of soil water retention as well as the unsaturated hydraulic conductivity function, and should be estimated under transient conditions (Hillel, 1998; Bear and Cheng, 2009). *In situ*-implemented sensors can obtain data for the state variables (e.g. water content and pressure head) in their natural environment, implicitly including interactions between different soil layers and across scales (Wollschläger et al., 2009). Inverse modeling, in which models are calibrated using measured variables, has gained popularity for estimating the hydraulic functions of the unsaturated zone. These models can then reproduce independent measurements as validation (Jacques et al., 2002; Ritter et al., 2003; Wöhling et al., 2008; Wollschläger et al., 2009; Chen et al., 2014; Turkeltaub et al., 2014).

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http://dx.doi.org/10.1016/j.jhydrol.2015.01.026
0022-1694/

Development of a vadose zone-monitoring system (VMS) has enabled continuous acquisition of information on the temporal variations of the vadose zone water-content profiles (Dahan et al., 2007, 2009; Rimon et al., 2007; Baram et al., 2012, 2013; Turkeltaub et al., 2014), the chemical evolution of the pore water at multiple depths from land surface and the root zone to the water table (Dahan et al., 2009; Rimon et al., 2011a; Baram et al., 2012; Turkeltaub et al., 2014), and water pressure (Rimon et al., 2011b).

The objective of this study was to investigate the relationship between precipitation and groundwater recharge in a sand dune area. A calibrated unsaturated flow model was used to provide detailed transient deep vadose zone data and long periods of climate data. The data for the calibration process were obtained by an array of VMSs which were installed in various orientations at the sand dune site. Previous studies showed that no significant field-scale (meters) preferential flow dominates the percolation process at the site and that the subsurface is made up of relatively homogeneous and horizontal layers (Rimon et al., 2007). These conclusions were the basis for the uniform vertical unsaturated flow model that was calibrated to the VMS transient data in this work. The calibrated model allowed calculating recharge fluxes with high temporal resolution. The relationship between precipitation and recharge was then statistically analyzed at monthly and yearly resolutions.

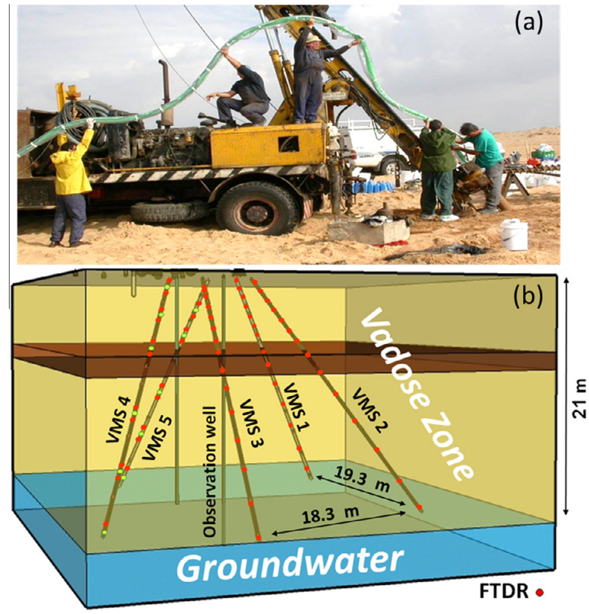

Fig. 1. The sand-dune site: (a) the drilling rig during the installation of the long flexible vadose-monitoring system (VMS; green) in the slanted borehole. (b) The VMSs in their different orientations in the slanted boreholes and location of the observation well (modified from Rimon et al., 2007). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Research area and instrumentation setup

The study site was located in the southern coastal plain of Israel, south of the city of Ashdod (34°38′26″E 31°46′7″N). A Mediterranean climate prevails at the study site, the summers are completely dry, and the rainy season extends from October to April, with an annual precipitation average of 450 mm (spatial interpolation of the nearest station's data provided by the Israeli Meteorological Service, 2014 [IMS]). The average temperature in the hottest month is 31.2 °C (August) and in the coldest month, 17.8 °C (January) (IMS). Reference evapotranspiration (ET) rates calculated according to the Penman–Monteith method (suggested by the Food and Agriculture Organization) range from 1.5 mm day^{-1} (January) to 5.7 mm day^{-1} (July) (IMS). The site is characterized as a sand dune area with a moderate slope. Sparse herbaceous vegetation grows in the inter-dune area, but the dunes themselves are bare sand (Fig. 1). The coarse matrix of the sand dunes in the area (98% sand in particle-size distribution analysis) promotes rapid infiltration and prevents runoff during rain events. The shallow stratigraphy consists of Holocene sand dunes, calcareous sandstone, and clayey interlayers (Ecker, 1999). Rainwater infiltration through the sand dune recharges the phreatic sandy coastal aquifer. The water table at the monitored site is approximately 21 m below ground surface.

Four VMSs were installed at the sand dune site, enabling continuous measurements of water contents at multiple depths using 15 flexible time-domain reflectometry (FTDR) sensors. Two of the VMSs were instrumented with vadose zone pore water-sampling ports (VSPs) which were used for either frequent sampling of the vadose zone pore water or measuring the pressure head at multiple depths. The system has been previously described (Dahan et al., 2009; Rimon et al., 2011a); herein we provide a brief overview of the system for completeness. The monitoring system is composed of a flexible sleeve made of a thin polyvinyl chloride liner, hosting several customized FTDR probes (Dahan et al., 2003) for water-content measurements and VSPs (Rimon et al., 2011a). The monitoring systems were installed in uncased, small-diameter (15 cm), slanted (35°) boreholes penetrating the 21-m thick vadose zone of the study site. Consequently, the FTDR probes and VSPs were aligned along the slanted borehole's upper sidewall facing the undisturbed sediment column, which extended from the probe location on the top wall of the borehole to land surface. Each of the probes and sampling ports represents a different undisturbed profile because every probe and sampling port is shifted both vertically and horizontally from the next. Vertical boreholes were drilled next to the VMSs for accurate sediment sampling. Particle-size distributions of these samples were analyzed by hydrometer method (Klute, 1986). One of these boreholes was then completed as a piezometer with a screen interval of 5 m below the water table.

2.2. Model setup

To have an accurate tool for analyses of the precipitation–recharge relationship, a calibrated unsaturated flow model was used for groundwater-recharge simulations. The Richards' equation was implemented to account for water flow in the vadose zone of the sand dune, and the unsaturated hydraulic functions of the different layers were described by the van Genuchten–Mualem formulation (Mualem, 1976; van Genuchten, 1980). The parameters of the hydraulic functions were inversely calculated by the HYDRUS-1D code (Šimůnek et al., 2009) which numerically simulates the 1D form of the Richards' equation and includes a Marquardt–Levenberg-type (Marquardt, 1963) parameter-optimization algorithm for inverse estimation.

The sand-dune model was calibrated to transient data from the deep vadose zone. These data contained temporal and spatial variations in the water contents of the deep vadose zone at multiple depths and locations. These variations are a consequence of rainwater infiltration into the soil and drainage of the unsaturated zone down to the phreatic aquifer. The hydraulic properties of the layers in the modeled domain were defined according to particle-size distribution analyses as well as measured water contents.

The model's domain was discretized into 250 nodes, with a finer grid close to the surface. The number of nodes and density of the