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Infiltration in layered loessial deposits: Revised numerical simulations and recharge assessment

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SUMMARY

The objective of this study is to assess recharge rates and their timing under layered loessial deposits at the edge of arid zones. Particularly, this study is focused on the case of the coastal plain of Israel and Gaza. First, results of a large-scale field infiltration test were used to calibrate the van Genuchten parameters of hydraulic properties of the loessial sediments using HYDRUS (2D/3D). Second, optimized soil hydraulic parameters were used by HYDRUS-1D to simulate the water balance of the sandy-loess sediments during a 25-year period (1990–2015) for three environmental conditions: bare soil, and soil with both sparse and dense natural vegetation.

The best inverse parameter optimization run fitted the infiltration test data with the RMSE of 0.27 d (with respect to a moisture front arrival) and R^2 of 96%. The calibrated model indicates that hydraulic conductivities of the two soil horizons, namely sandy loam and sandy clay loam, are 81 cm/d and 17.5 cm/d, respectively. These values are significantly lower than those previously reported, based on numerical simulations, for the same site.

HYDRUS-1D simulation of natural recharge under bare soil resulted in recharge estimates (to the aquifer) in the range of 21–93 mm/yr, with an average recharge of 63 mm/yr. Annual precipitation in the same period varied between 100 and 300 mm/yr, with an average of 185 mm/yr. For semi-stabilized dunes, with 26% of the soil surface covered by local shrub (*Artemisia monosperma*), the mean annual recharge was 28 mm. For the stabilized landscape, with as much as 50% vegetation coverage, it was only 2–3 mm/yr. In other words, loessial sediments can either be a source of significant recharge, or of no recharge at all, depending on the degree of vegetative cover. Additionally, the time lag between specific rainy seasons and corresponding recharge events at a depth of 22 m, increased from 2.5 to 5 years, and to about 20 years, respectively, with an increasing vegetative cover. For this reason, and also likely due to a great depth of loessial sediments, no correlation was found between annual recharge and annual precipitations of the same year or subsequent years. Similarly, no differences were found between summer and winter recharge fluxes. Instead, numerical simulations indicated continuous year-round recharge of the aquifer. We conclude that the layered subsurface acts as a short-term (annual) and long-term (multi-annual) buffer to smooth sudden precipitation/infiltration events. Vegetation conditions can help in predicting long-term recharge rates (as percentage of annual precipitation), which in turn need to be considered when assigning recharge characteristics in regional assessments and models.

1. Introduction

Recharge estimations play an important role in the management and research of groundwater systems. The magnitude and timing of groundwater recharge with respect to the corresponding infiltration events are controlled by climatic and geological factors, as well as the depth to the water table, and have long been of scientific and practical interest (e.g., Wu et al., 1996; Scanlon et al., 2006). Recharge can be estimated by various methods, which should be selected based on the climate zone (arid/humid), expected fluxes, the spatial scale of the aquifer, and the studied time scale (Scanlon et al., 2002a). Such a task should also consider the data availability in terms of soil hydraulic properties and climatic data (e.g., precipitation and evaporation time series).

Physically based models, such as those solving the Richards' equation for water flow in the vadose zone and water balance of surficial sediments, have often been used for estimations of groundwater recharge under various conditions (Wu et al., 1996;

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Scanlon et al., 2002b; Kurtzman and Scanlon, 2011; Leterme et al., 2012; Turkeltaub et al., 2015). These models require the knowledge of soil water retention and unsaturated hydraulic conductivity functions for all soil horizons. Nevertheless, as such knowledge exists (or is measured) only in rare cases, inverse modeling, in which numerical models are calibrated using measured flow-related variables, has gained popularity for estimating the hydraulic functions characterizing the unsaturated zone (Hopmans et al., 2002; Vrugt et al., 2008). Inverse models are then tested by their ability to reproduce independent measurements (Jacques et al., 2002; Ritter et al., 2003; Turkeltaub et al., 2015). Inverse modeling has several important advantages over other methods of estimating soil hydraulic properties. These mainly include (a) the ability to simultaneously estimate both the soil water retention and unsaturated hydraulic conductivity function from a single transient experiment, and (b) the fact that similar numerical models are used both for estimation of soil hydraulic properties (calibration) and for predictive forward modeling (assessment of recharge) (e.g., Hopmans et al., 2002).

Loessial soils are regarded by many as transmissive and rechargeable (Lin and Wei, 2006; Seiler and Gat, 2007; Aish, 2014). Nevertheless under some vegetation and climate conditions they might "*act as an impervious barrier to recharge*" (Weinthal et al., 2005). The objective of this paper is to provide a physically based assessment of recharge rates under loessial soils for arid climate and vegetation. We use the case of the coastal aquifer bounding Israel and the Gaza strip. Large parts of this aquifer are covered by loess and loessial sediments.

The thorough data set collected during a large infiltration test in this area, as reported by Gvirtzman et al. (2008), is first used to quantify the hydraulic conductivities and van Genuchten retention parameters of the loessial sediments of the studied area. Second, calibrated soil hydraulic properties and long-term meteorological data are used to assess the long-term natural recharge to the underlying sandy aquifer. These two modeling stages are sequentially discussed in separate sections. Finally, insights obtained using this recharge model are discussed in relation to previously used models and empirical recharge estimations of the same aquifer. The conclusions obtained in this study for the coastal plain underlying Israel and Gaza Strip are relevant for other phreatic aquifers overlain by a thick, layered unsaturated-zone, especially those within a similar arid climate.

2. Study area

While it is also relevant for other areas on the edge of arid-climate zones, the study focuses on the area covered by sandy loess soils south of the Gaza Strip (Fig. 1). In this area, a relatively thick (>20 m) layer of loessial deposits covers permeable sandy layers of the coastal aquifer (Fig. 1b). The water table is at a depth of about 25–35 m, and the hydraulic gradient is toward the Mediterranean coast, i.e., to the NW.

The term 'loessial deposits' is used here to describe the sandy grain-size loess, according to the Yaalon and Dan (1974) definition, and to distinguish it from silty grain-size loess. The sediments accumulated during the Late Pleistocene period when desert storms brought sands from the northern Sinai Desert to the area (Yaalon and Dan, 1974; Crouvi et al., 2010). Since the distance from the parent material to the accumulation site is relatively short, these wind-blown sediments maintained a fairly coarse-grain composition, contrary to the classic silt-size loess sediments (Crouvi et al., 2010). Nevertheless, the grain size distribution in the loessial sediments is highly variable and depends on the wind speed (Crouvi et al., 2010). During periods of intense winds, active eolian abrasion of the sand grains increased, silt-size sediments were imported, and vice versa. Gradually, a layered sandy loess deposit was accumulated.

The area is dominated by the Mediterranean climate, with dry and hot summers and a rainy season between October and April. The average annual precipitation is about 200 mm/yr. At En Habesor meteorological station (#144872, Israel's Meteorological Service (IMS) database, see location in (Fig. 1a)), an average precipitation of 185 mm/yr was recorded during the last 25 years (1990–2015). The cumulative annual potential evaporation exceeds 1800 mm.

The dominant species in the area is a desert dwarf shrub, *Artemisia monosperma* (Bar Kutiel et al., 2016). It has an important role in the dune stabilization process, and covers up to 16%, 16–36%, and 36–65% of the total area of mobile, semi-stabilized and stabilized dunes, respectively. *A. monosperma* develops a unique root system in response to the accumulating or dispersing sands around it. Similar to other species of dune vegetation, its roots seldom exceed a depth of 3 m, but extend laterally to accommodate any available water from the 'open matrix' in-between neighboring shrubs (Bar Kutiel et al., 2016).

The observed run-off from sandy loess soils in the region is very small (Yair, 1990; Givati and Atzmon, 2009; Eshtawi et al., 2015). For the entire catchment of the ephemeral Besor River, which is covered in large parts by sandy loess sediments, the run-off coefficient for 1985/6–2009/10, defined as % of annual precipitation, was only 1.3% (Givati and Atzmon, 2009). For comparison, the average run-off coefficient over the entire western drainage system of Israel in the same period was 4.4%.

2.1. 2004 Infiltration test

A large trench infiltration test was conducted within the study area in 2004 by Gvirtzman et al. (2008). We only provide here a short description of the infiltration test, its set-up, the measurements made, and the obtained results that are relevant to the current study. Detailed information about the experiment can be found in Gvirtzman et al. (2008).

An elongated trench (3 m wide by 17 m long at the base) was excavated in the loessial section, and its sloping edges were covered by PVC sheets. Four bores (marked 'A' through 'D') were drilled in the vicinity of the trench midline (Fig. 2). Each was equipped with 7–8 TDR probes at different depths, which monitored the temporal changes in the water saturation. The probes were numbered from top to bottom (i.e., probe C2 is deeper than probe C1, etc.). Due to technical issues, only data of 22 sensors was collected, as noted in Fig. 2.

Soil and sediment samples taken from these bores allow for detailed characterization of the profile. Soil moisture, bulk density, porosity, content of fines (<0.075 mm), and other parameters were measured every 2 m (Gvirtzman et al., 2008; Hatzor et al., 2009). Overall, the loessial sediment profile is stratified, with alternating horizons classified as silty sand, clayey sand, and low plasticity clay ('SM', 'SC', and 'CL', respectively) according to the Unified Soil Classification System (USCS). The exact description of the sediment profile, as well as soil physical properties, slightly varied from bore to bore.

In March 2004, following the end of the winter season, the trench was flooded with 1 m of water for 17 days. TDR readings were taken in decreasing frequencies during 20 days of the experiment. The analysis of water content measurements shows that the wetting front propagates below the trench in an 'onion-shape' pattern. The data further indicates that the wetting front reached the lowest probe (C8), located 20 m below the trench base, between