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The effect of hydrogeological conditions on variability and dynamic of groundwater recharge in a carbonate aquifer at local scale

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SUMMARY

Groundwater recharge in fractured karstic aquifers is particularly difficult to quantify due to the rock mass's heterogeneity and complexity that include preferential flow paths along karst conduits. The present study's major goals were to assess how the changes in lithology, as well as the fractured karst systems, influence the flow mechanism in the unsaturated zone, and to define the spatial variation of the groundwater recharge at local scale. The study area is located within the fractured carbonate Western Mountain aquifer (Yarkon-Taninim), west of the city of Jerusalem at the Ein Karem (EK) production well field. Field monitoring included groundwater level observations in nine locations in the study area during years 1990–2014. The measured groundwater level series were analyzed with the aid of one-dimensional, dual permeability numerical model of water flow in variably saturated fractured-porous media, which was calibrated and used to estimate groundwater recharge at nine locations. The recharge values exhibit significant spatial and temporal variation with mean and standard deviation values of 216 and 113 mm/year, respectively. Based on simulations, relationships were established between precipitation and groundwater recharge in each of the nine studied sites and compared with similar ones obtained in earlier regional studies. Simulations show that fast and slow flow paths conditions also influence annual cumulative groundwater recharge dynamic. In areas where fast flow paths exist, most of the groundwater recharge occurs during the rainy season (60–80% from the total recharge for the tested years), while in locations with slow flow path conditions the recharge rate stays relatively constant with a close to linear pattern and continues during summer.

1. Introduction

Unsaturated flow mechanisms and groundwater recharge in fractured carbonate aquifers are highly influenced by rock mass diversity. The deposition processes of sedimentary bodies vary in time and location (Wright and Burchette, 1996). These processes are the basis for facial distributions in the rock mass which is later affected by various physical and chemical processes. Water flow through the rock mass, both in the vadose and the saturated zones, is influenced by the media hydraulic properties' spatial deviations (Montazer and Wilson, 1984; Flint et al., 2001a; Hartmann et al., 2014; Mahmud et al., 2015). Low permeability layers that are located in the vadose zone and act as impermeable or partly impermeable flow boundaries within the aquifer are a basis for different scales perched water bodies in the unsaturated zone (Flint et al., 2001b; Kordilla et al., 2012; Heaton et al., 2012; Allocca et al., 2015). Heterogeneity of rock properties affects spatial and temporal distribution of recharge and subsurface flow dynamics during varying hydroclimatic conditions (Hartmann et al., 2015).

The hydrogeological section in Fig. 1 illustrates the major pathways of water flow in the unsaturated zone flow of karst aquifers. Within this section, two flow paths' end members can be observed. In the first (A), fast flow occurs from surface sources, such as precipitation and runoff, by karst and fault conduits in the unsaturated zone. The second end member (B) marks slow flow conditions in which the flow path passes through matrix and unkarstified fissures and encounters low permeability layers that delay the flow front. The described conditions are common in the thick phreatic parts of sedimentary aquifers and present bigger challenges in fractured carbonate aquifers where preferential flow occurs. In such sections, significant rapid groundwater-level fluctuations that are related to the first end member can occur. Examples of large

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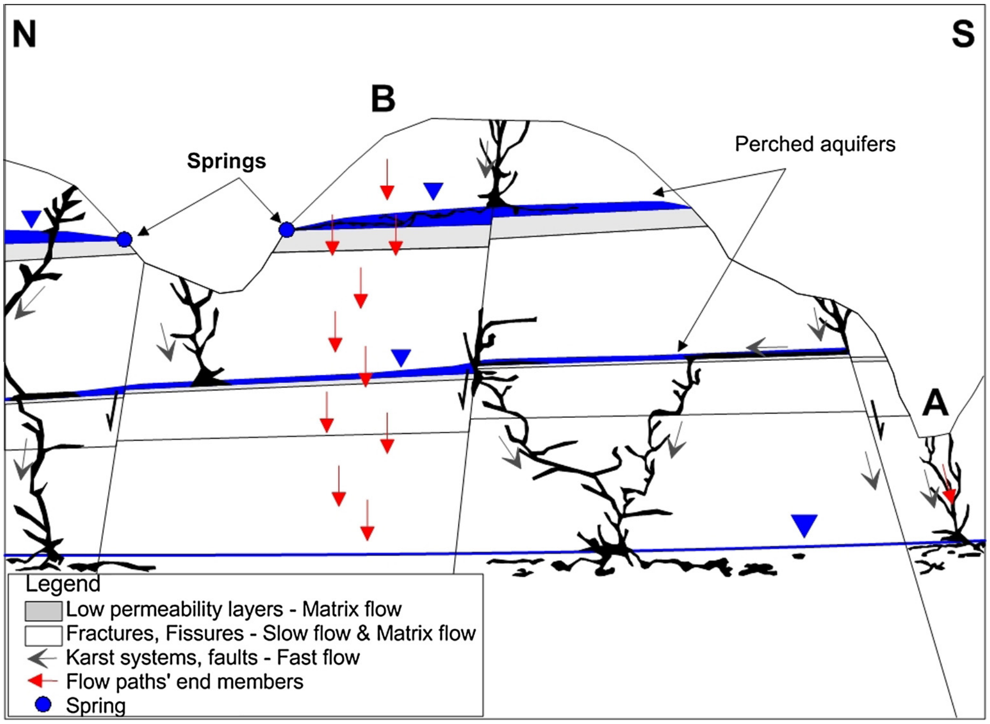

Fig. 1. Schematic cross-section of a fractured carbonate aquifer. The recharge and the unsaturated flow mechanism are affected by the occurrence of low permeability layers; also shown are the distribution of fractures and fissures within the carbonate matrix and karst and the fault conduits' occurrence. Flow paths (red arrows): (A) fast flow through karst and fault conduits along a thin unsaturated zone; (B) slow flow through matrix and fissures across low permeability layers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

groundwater level fluctuations are the Hettangian limestone plateau aquifer in France, where several tens of meters of water level response to precipitation was documented (Larocque et al., 2000; Debieche et al., 2002; Lee et al., 2006).

Groundwater levels are frequently used to assess recharge (Healy and Cook, 2002). Unfortunately, the interpretation of the water table fluctuation in fractured media and its use in the estimation of recharge is a difficult task since they may both be affected by several inhibiting factors such as evapotranspiration, entrapped air and/or atmospheric pressure (Scanlon et al., 2006; Healy, 2010; Nimmo et al., 2015). Allocca et al. (2015) reported a local scale, recharge study in a karst aquifer in southern Italy using the Episodic Master Recession method, an improved version of the Water Table Fluctuation method. Guardiola-Albert et al. (2015) tested six different methods to provide the most plausible range of recharge rates in a karst aquifer during wet periods. While these and other studies are aimed at estimating episodic recharge, we hypothesize that groundwater recharge, in areas with thick unsaturated zone, is persistent and continuous into the dry season and even into the following years.

Groundwater levels in the study area (the Ein Karem well field, west of Jerusalem, Israel) exhibit the diversity of response to precipitation. Groundwater level fluctuations ranging between a few meters to several tens of meters were observed within short distances. Since all the boreholes in the Ein Karem well field penetrate the same water-bearing formations, it is suggested that this diversity is related to rock mass variations due to facies changes and/or subsequent mechanical and chemical evolution (mostly fractures and karst). Early water balance calculations and recharge values were assessed by Goldschmidt and Jacobs (1958) based on the Yarkon and Taninim springs' base-flow measurements during the hydrologic years 1943/44–1953/54. Later studies, such as Goldshtoff and Ben Zvi (1972), Baida and Zukerman (1992) and Zukerman and Shachnai (1999), presented a similar approach, which was summarized by a linear relationship between yearly precipitation rate and recharge values. In determining the recharge coefficient, some studies considered spatial climate variations (Dafny et al., 2010; Wollman et al., 2010). Berger (1999) and Sheffer (2009) included soil saturation, and Sheffer (2009) also conducted field measurements and experiments that supported the aquifer's dual permeability properties.

In this paper we present the results of the combined study of the lithological features of the fractured and karst vadose zone – aquifer system, monitoring groundwater level, and mathematical modeling to access temporal and spatial variation of groundwater recharge at the local scale. Results show how the lithology changes influence flow mechanisms in the unsaturated zone and the spatial and temporal variation of groundwater recharge rates. This contributes to an improved understanding of the subsurface flow processes and provides valuable information for water planning authorities.

2. Hydrogeology

2.1. General geological setting

The fractured carbonate Western Mountain aquifer extends from south of the Carmel Mountains, in the north, to the Sinai Desert in the south and from the Judea and Samaria Mountains in the east to the Mediterranean coastline in the west (Fig. 2). The aquifer is composed of the Judea group that mainly contains carbonate sections aged Late Albian to Turonian (Arkin and Braun, 1965; Arkin and Hamaoui, 1967; Ben Gai et al., 2007) (Fig. 3). The group represents a stable carbonate platform depositional sequence (Sass and Bein, 1982). Syndepositional and postdepositional environmental conditions created spatial variations in carbonate contents that created different basic settings for the aquifer's development.