Groundwater flow along and across structural folding: an example from the Judean Desert, Israel

Leehee Laronne Ben-Itzhak¹, Haim Gvirtzman*

Institute of Earth Sciences, The Hebrew University of Jerusalem, Givat Ram Campus, Jerusalem 91904, Israel

Received 25 March 2004; revised 14 January 2005; accepted 1 February 2005

Abstract

The considerable influence of the geological structure on groundwater flow regime is exhibited in the thick carbonate aquifer beneath the Judean Desert, Israel. Groundwater flow is diverted from the general steep hydraulic gradient, creating a subsurface 'river-like' meandering flow pattern. The structure of the extensive-folded anticlinorium forces groundwater flow through synclinal axes in the upper aquifer and in places it overflows from one to an adjacent syncline. Groundwater outflows are at Tsukim, Kane, Samar and En-Gedi springs near the Dead Sea shore and by sub-surface flow across the Graben faults towards the Dead Sea.

In this study all available data are integrated and processed, first ever, to form a complete representation of the three-dimensional hydrostratigraphy and hydrogeology. Using numerical modeling (MODFLOW), we analyzed quantitatively the flow regime, leakage rates between upper and lower sub-aquifers and between adjacent sub-basins, the groundwater mass balance, and aquifer hydraulic properties.

This study has practical implications regarding recent groundwater management, future possibilities of groundwater development for the benefit of both Israelis and Palestinians residing in the area, and conservation of nature reserves located along the Dead Sea.

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Keywords: Groundwater; Flow; Aquifer; Modeling; Dead Sea; Israel; MODFLOW

1. Studied area

1.1. Geographical location

The main hydrogeological water-divide in Israel runs along the mountain range, from the

¹ Present address: Hydrological Service, Water Commission, Jerusalem, Israel.

* Corresponding author. Fax: +972 2 5662581.
E-mail addresses: leeheel@water.gov.il (L. Laronne Ben-Itzhak), haimg@vms.huji.ac.il (H. Gvirtzman).

Galilee Mountains in the north, through the Samaria and Judea Mountains in the center, to the Negev Mountains in the south. This water-divide separates between groundwater flow towards the Mediterranean Sea in the west and towards the Dead Sea Rift Valley in the east. Our research area is the Judean Desert, located in the eastern side of the Judean Mountains (Fig. 1). This region is characterized by an altitudinal drop from almost 1000 m asl (above sea level) at the headwaters to the current Dead Sea water
level of −415 m asl, over a horizontal distance of 25–30 km. A major part of the descent is constrained within the steep cliffs above the Dead Sea shore. This research area displays a rain-shadow: the mountains encounter up to 750 mm of precipitation annually with an eastward decrease to less than 100 mm/yr at the Dead Sea. Surface water flow is characterized by short
flood events in sub-parallel eastward flowing canyons. This study deals with the aquifer beneath the Judean Desert, a thick carbonate aquifer comprised of an upper phreatic unit overlying a confined unit, separated by a thin aquitard.

1.2. Geology

The stratigraphic column includes formations of the Judea, Mt. Scopus and Dead Sea Groups of Lower Cretaceous to Holocene ages. Fig. 1 shows a geological map of the research area and Fig. 2 presents a typical

![Stratigraphy diagram](image-url)
stratigraphic columnar cross section. The Judea Group is exposed mostly in the western part of the area. It consists mainly of limestone and dolomite with some marl and chalk. Its thickness is greatest (ca. 900 m) in the Judea Mountains and decreases towards the south, east and west to a minimum of ca. 600 m near En-Gedi. The terminology for the Judea Group formations in the western and in the eastern parts of the research area is different (Fig. 2). Yet, there is good lithological and stratigraphical correlation between the formations of these terminologies (Begin, 1972). Mt. Scopus Group, essentially chalk, is exposed throughout most of the desert plateau and includes formations of Santonian to Paleocene ages. Its thickness varies from ca. 100 m in anticlinal regions to 400 m in the synclines. The Pliocene-Holocene Dead Sea Group is exposed along the Dead Sea shore. It is composed of conglomerate, silt, clay and marl as well as halite, chalk and some gypsum.

The dominant structures in the area are of two types: folds and fractures; each is related to a different stress field (Eyal and Reches, 1983). The folds are the product of the Syrian Arc stress field, with dominating maximum horizontal compression trending W to WNW, while most of the fractures are related to the Dead Sea stress field, with dominating horizontal extension trending E to ENE. The folds are characterized by a series of asymmetric anticlines and synclines with axes plunging on the average to the NE. The two main structures of this type are the Hebron and the Ramallah Anticlinoriums, in which the northwestern flanks are steeper than the southeastern flanks (Fig. 3).

The Dead Sea Basin is the largest fracture-related structure in the region. It is a rhomb-shaped pull-apart basin, the deepest part of the Dead Sea transform (Garfunkel and Ben-Avraham, 1996). It is bounded to its north and south by two major strike-slip faults and along its western and eastern margins there is a belt of sub-parallel normal faults. The western fault is the dominant morphological feature in the studied area, creating a steep cliff near the Dead Sea shore. This fault places the Judea Group carbonates, which comprise the cliff, against the Dead Sea Group in the east. Other smaller faults and joints exist throughout the entire area, some of which are shown on the geological map. Two groups of fracture strike directions trend NNW and NNE, with fracture density increasing towards the Dead Sea (Sagy, 1999).

1.3. Hydrology

Previous studies (Rofe and Raferty, 1965; Rosenthal, 1978; Rosenthal and Kronfeld, 1982; Kroitoru, 1987; Guttman and Rosenthal, 1991; Kronfeld et al., 1992) have shown that the Judea Group freshwater aquifer is divided into two horizons (Fig. 2): (i) an upper sub-aquifer of Weradim and Amminadav Formations (Tamar and Zafit Formations in the east), and (ii) a lower sub-aquifer of Kesalon, Giv’at Ye’arim, Kefira and parts of Soreq Formations (Hevyon Formation in the east). Separation between the upper and lower sub-aquifers occurs within the Moza and Bet-Me’ir Formations (Guttman and Zuckerman, 1995; Guttman, 2000), with groundwater levels in the upper aquifer higher than those in

Fig. 3. A structural map of the top Judea Group showing the main folds and faults (based on Fleischer and Gafsou, 1998). The fold axes trend NE and dictate the groundwater flow pattern.
the lower aquifer throughout most of the area. Separation between the lower Judea Group sub-aquifer and the deeper (saline) aquifers exists mostly at the western part of the studied area (Qatana Fm.), but due to facial changes it becomes thinner and disappears at the east. A third freshwater sub-aquifer (an uppermost horizon) exists in the Turonian formations, only in a northern part of the research area. It is characterized by fast flowing groundwater within a well-developed karstic system, and it is discharged at the Jericho and Wadi Kelt Springs (north of the study area). This sub-aquifer is local, partially perched, with no pumping wells; thus, it is excluded from the present research.

The aquifer is fed solely by rainwater falling during the winter season. Before pumping was initiated, the aquifer had discharged naturally through springs along the Dead Sea shore and as subsurface leakage into the Dead Sea Group Aquifer while crossing the rift faults. Groundwater mass balance calculations of the Judea Group aquifer are usually based on estimations of water outputs, rather than on water inputs, because no accurate data exists on the distribution of evapo-transpiration. The average discharge of the aquifer in the studied area has been estimated to be about 85 million cubic meters per year (MCM/y), as is detailed below.

The three largest springs in the research area are: Tsukim (Fescha), Kane and Samar (Fig. 1). Their water originates from both sub-units of the Judea Group aquifer, but the springs emerge from the conglomerates of the Dead Sea Group in the downthrown side of the western graben faults. The springs are a mixture of meteoric fresh water with a relatively small amount of ascending deep brine (Stanislavsky and Gvirtzman, 1999). Different rough estimations were provided for the annual discharge of the largest one, the Tsukim spring, ranging between 30 and 50 MCM/y (Fink, 1973; Shachnai et al., 1983; Greenboim, 1992, 1993); however based on recent accurate measurements, Rophe (2003) reported about 65 MCM/y (after the 2003 rainy season). Estimations of Kane and Samar discharges ranged between 30 and 40 MCM/y (Guttman and Simon, 1984; Greenboim, 1992, 1993). A few smaller springs are located along the Dead Sea shore: Mazor, Yesha, Kedem, Kalia, and Kumeran, with an estimated average total discharge of 3.6–5.0 MCM/y (Guttman and Simon, 1984). These are also considered to be of the same sources, perhaps with different mixing ratios between the fresh and brine sources. In addition, there are four fresh water springs in the En-Gedi area, located on the upthrown western side of the main fault: En-Gedi, Shulamit, David and Arugot. Their water emerge from the Zafit Formation (upper sub-aquifer) and their discharge is relatively small, a total of 3–4 MCM/y (Nature Reserves and Parks Authority, pers. comm.). There are no direct measurements of subsurface leakage into the Dead Sea; the only available information is from water balance estimates and models and from indirect observations (Fink, 1973; Guttman, 1984; Gilad, 1993). During measurements of spring discharge there have been observations of water outflow from the sea floor, adjacent to the shoreline. Estimations vary from negligible amounts in the Kalia area, to 5–6 MCM/y in the shore sections where the major springs are present, and up to dozens of MCM/y in the deeper Dead Sea Group Aquifer, which is beneath the elevation of the springs. Most estimates, however, are in the low range.

Tens of wells (observation, production and a few oil wells) have been drilled in the Judean Desert. Table 1 summarizes their physical characteristics. Most of the production wells are located in three pumping fields: Herodion, Jerusalem and Mitzpe Jericho (Fig. 1). A few new Palestinian production wells have been added in recent years, mostly in the Herodion area. The increased abstraction, along with a decrease in precipitation during recent years, has resulted in a substantial lowering of the water table.

Chemical analyses of groundwater from wells indicate that the water is of meteoric origin, with salinities lower than 100 mgCl/l in the western part of the area near the recharge zone, and with a wider range of salinities (30–600 mgCl/l) along the eastern boundary of the aquifer (Kronfeld et al., 1992; Guttman, 2000 and TAHAL Consulting Engineers Ltd, files). At Mitzpe Jericho, the salinity difference between the two sub-aquifers is the largest, with approximately 430 and 5000 mgCl/l in the upper and lower sub-aquifers, respectively (Mitzpe Jericho 3, from Guttman and Rosenthal, 1991; Guttman, 2000). Salinities of the Dead Sea springs are
higher; for example, at Tsukim Springs salinity ranges between 1700 to over 40,000 mgCl/l (Mazor and Molcho, 1972; Greenboim, 1992, 1993).

Finally, it should be noted that in principle groundwater in the studied area is found in three different aquifers: (i) the shallow Dead Sea Group Aquifer, composed of the rift sediment fill; (ii) the Judea Group Aquifer, which is the subject of this study; and (iii) the deep Kurnub Group Aquifer of Lower Cretaceous age, which lies beneath the Judea Group, and is not exposed in this area. The Judea Group Aquifer contains more than 95% of the total discharge in this area and, thus, this research deals only with it. Nevertheless, interactions with the other aquifers surely exist.

### 1.4. Research objectives

Several studies have focused on the groundwater flow field through the carbonate aquifer beneath the Judean Desert. One of the first studies (Arad and Michaeli, 1964) suggested a uniform west to east flow, parallel to the hydraulic gradient, because no contradicted observations were available. Groundwater levels vary from ca. 400 m at the mountains in the west to −400 m at the Dead Sea in the east, along a horizontal distance of 25–30 km, generating a very steep hydraulic gradient of about 3% on average. However, such a steep hydraulic gradient, especially within a karstic carbonate aquifer, is rarely found and, in fact, it is very difficult to be naturally maintained.
under the given small amounts of recharge and discharge. Moreover, such a gradient should cause a continuous groundwater leakage from the exposed aquifer along the entire Dead Sea shore, which in reality does not occur. As stated earlier, most of the discharge occurs in three large springs concentrated in the northern part of the Dead Sea shore.

Subsequent studies have suggested a non-uniform groundwater hydraulic gradient, where the flow pattern is influenced by the geological structure (Burstein, 1970; Fink, 1973). This may cause meandering flow paths, even if the general direction of the gradient is from west to east. Fink (1973) emphasized that there was not enough data to evaluate this hypothesis.

Recent studies (Guttman and Zuckerman, 1995; Guttman, 2000) have constructed a two-dimensional (one horizontal layered) numerical simulation of groundwater flow in this region. They addressed the distinct locations of discharge by constructing openings, representing springs, in the otherwise no-flow eastern boundary. This has caused some problems of a high groundwater table along the cliff south of Tsukim Springs, which cannot be bounded by a no-flow boundary, since the cliff is exposed at these elevations. In any case, these studies did not address the relationship between the geological structure and the flow field, which is the objective of this study.

In this study all available data are integrated and processed, first ever, to form a complete representation of the three-dimensional (3D) hydrostratigraphy and hydrogeology. Thereby, we demonstrate how the geological structure influences the flow pattern in the upper and lower sub-aquifers. Moreover, we explain conceptually and analyze quantitatively (using numerical modeling) why springs are located only in the northern corner of the Dead Sea, and why groundwater does not discharge continuously through the exposed aquifer along the entire cliff front.

2. Conceptual model

The accuracy of a hydrogeological model depends on precise definition of the aquifer physical boundaries and on a proper estimation of water mass balance. These objectives are usually met through a numerical model development. However, in this case, the studied aquifer is just a part of the entire Eastern Mountain Aquifer (draining towards the Jordan and Dead Sea Rift Valley) and, thus, it was important to meet these objectives at a former stage of conceptual model establishment, refining them later.

2.1. Boundary construction

The studied area was bound and divided into sub-drainage basins according to its geological structure using a GIS ArcView program. The top Judea Group structural map (Fleischer and Gafsou, 1998) was transformed into a GIS grid format. The structural geometries of the other three horizons (base of the upper sub-aquifer, and top and base of the lower sub-aquifer) were established by subtraction of formation isopach maps. Isopach maps were drawn by interpolation and integration of all available data of formation thickness (boreholes and field records).

Given the geometry of the base of the upper sub-aquifer, which is a structural surface, and assuming that it is sealed, then groundwater flow may be described under some conditions (as is explained hereafter) as surface runoff. In other words, groundwater is expected to flow only according to surface slopes, in the direction of the steepest descent. Based on this assumption, we have used GIS automated routines for watershed and stream network delineation. The precise hydrological water divides were determined and three major sub-drainage basins were delineated (Fig. 4). As is drawn, many of the ‘stream’ lines match syncline axes and many of the sub-basin boundaries match anticline axes. The sub-basins were named according to the springs they feed, namely: Tsukim Basin, Kane-Samar Basin and En-Gedi Basin. This analysis is applicable only if groundwater flows along the syncline axes as surface water flow in open channels. Definitely, when the saturated zone becomes thicker and groundwater table becomes higher than the adjacent anticline axes, some groundwater will overflow across the anticline barrier; under these conditions groundwater moves from one sub-basin to another. This analysis is valid with some exceptions, only at the western side of the aquifer, where it is phreatic and the saturated zone is thin. As moving eastward, where the aquifer is confined, groundwater flow direction is dictated only by the hydraulic gradient and not by the geological structure.
A small part of the western boundary is an exception, because the geological structure does not necessarily define the boundary. At the structural saddle between the northern tip of the Hebron Anticline and the southern tip of the Ramalla Anticline (Fig. 3), where Jerusalem City is located, the boundary is determined according to the steady-state hydraulic heads measured in wells. At the other parts of the western boundary, the saturated zone becomes thinner westward and disappears, having a wedge-shaped section. Thus, there is a physical separation between eastward and westward (towards the Mediterranean Sea) flows along the western boundary, and the anticline axes define the boundary. But, at the Jerusalem saddle, there is a continuity of the saturated zone across the structural-divide and the water divide is defined by the actual water table. In fact, the boundary may shift eastwards or westwards due to pumping at either side.

The northern and southern boundaries of the studied area (that coincide with the northern boundary of the Tsukim Drainage Basin and the southern boundary of the En-Gedi Drainage Basin, respectively) are flow lines, at least within the upper aquifer. At the lower aquifer we assume that the northern and southern boundaries are identical because no data are available to confirm or reject this assumption. As will be shown, the numerical model and the resulting water balance verify these assumptions.

The eastern boundary is the main western fault of the Dead Sea graben, through which the Judea Group aquifer is discharged.

2.2. Water mass balance

Calculations of rainfall replenishment were conducted using the GIS tool as well. The geological formations exposed in the study area are divided to those through which rainwater infiltrates, either to the upper or to the lower sub-aquifers, and to impermeable areas. The aquitard between the sub-aquifers is assumed to allow no water penetration, and runoff flows eastwards, penetrating into the upper aquifer. The same occurs with the lower aquiclude exposures, through which infiltration is eventually directed towards the lower aquifer. The Turonian exposures in the northwestern corner, through which rainwater penetrates into the uppermost aquifer and discharges at Wadi Kelt springs, were not included in the model and in the water mass balance calculations. The total replenishment areas of the upper and lower sub-aquifers are 450 and 82 km², respectively.

Recharge volume calculations were conducted by combining the replenishment areas with the average annual precipitation map using GIS. The infiltration equations used are based on previous studies conducted in the studied area (as integrated by Guttman, 2000). The relationships between replenishment \( R \) and precipitation \( P \) are:

For \( P < 300 \text{ mm/y} \) \( R = 0.15P \) \( (1) \)

For \( 650 \text{ mm/y} > P > 300 \text{ mm/y} \) \( R = 0.534(P - 216) \) \( (2) \)
For \( P > 650 \text{ mm/y} \quad R = 0.8(P - 360) \quad (3) \)

Considering rainfall distribution, the infiltration equations and the recharge areas, the resultant recharge volumes are 64.6 and 20.1 MCM/y into the upper and lower sub-aquifers, respectively.

The total discharge must equal the total recharge if a steady state is assumed. The steady state conditions used herein are those existing under natural conditions, namely, before major pumping started, prior to 1975. Based on available data (late 1960s and early 1970s), under these natural conditions, total discharge is \(-85\) MCM/y (Table 2).

Taking into account the large uncertainties in the recharge and discharge volumes, it is difficult to identify lack or excess of water resulting from flow across the northern and southern boundaries. It was, therefore, decided to leave these two boundaries at their locations and to check the plausibility of either no-flow or specified-flux boundaries in the numerical simulations.

### 3. Numerical model

#### 3.1. Grid construction

The numerical groundwater flow simulations were conducted using the MODFLOW code (McDonald and Harbaugh, 1988) with the GMS pre- and post-processor (Groundwater Modeling System; Brigham Young University). Elevations of the geological structural surfaces (top and base of the upper aquifer and base of the lower aquifer) were transformed from the GIS layers into the GMS grid. The constructed finite difference grid was composed of 79 rows by 47 columns, the dimensions of which varied according to geological considerations and locations of available hydrological data (Fig. 5). The upper aquifer was divided vertically into five layers to obtain an improved resolution and for the benefit of better graphical illustration of results, while the lower aquifer was represented by one, a sixth layer. The aquitard in-between was represented by a surface of zero thickness, having a restricted vertical hydraulic conductivity such that it represents the leakance between the upper and lower sub-aquifers (‘a quasi 3D approach’). The specific leakance at each location depends on fault density.

#### 3.2. Boundary conditions

Boundary conditions are shown in Fig. 5 as well. The lower boundary was defined as a no-flow type and the upper boundary as a phreatic surface. The western, northern and southern boundaries were of no-flow types (in fact, they were of specified fluxes that equaled zeros); the latter two were verified by sensitivity tests. Through the eastern boundary, discharge occurred only via springs and subsurface leakage to the Dead Sea. Accordingly, the boundary was divided into segments of these types. These segments were of mixed boundary types: flux depended on the difference between cell head and either spring elevation or Dead Sea elevation, using a specified conductance value for each of the segments. The heads of springs and of the Dead Sea were constants throughout the simulation (numerical experiments were involved with discharge rates...
only). En-Gedi Springs, which are not located on the eastern boundary, were defined as a sink within the model grid. The scale of this model was relatively coarse, representing basin patterns but not local ones; thus, there was not enough resolution to represent the four different springs at En-Gedi, especially since faults possibly dictate their exact location.

Assigning rainfall recharge to grid cells required converting the original infiltration locations, all above the unsaturated zone, into artificial infiltration locations, all below the unsaturated zone (MODFLOW solves flow equations only within the saturated zone). Otherwise, during the numerical iteration procedure, grid cells of the unsaturated areas were expected sometimes to dry, and thereby recharge water would be lost. This transformation process was a subject to some degree of individual interpretation; however, it was inevitable when working with this specific modeling code.

3.3. Steady-state calibration

The model was calibrated for natural steady state conditions, assuming constant rain, steady discharge and fixed groundwater table, neglecting seasonal fluctuations and/or relatively dry or wet years. Calibration was conducted through plentiful trial-and-error by varying aquifer hydraulic parameters and comparing calculated heads to those measured in wells, as well as comparing calculated fluxes across the eastern boundary to those estimated in the conceptual model. Best-fit results (Table 3) were obtained when the residuals between calculated and representative observed heads were reduced to the defined tolerance of $\pm 20$ m. Practically, the mean residual was 9.8 m, much less than the seasonal fluctuations. The resultant best-fit maps of water table elevation at the upper and lower sub-aquifers are summarized in Figs. 6 and 7 illustrates the best-fit 3D groundwater flow pattern.

The parameters that were changed during the calibration process were the horizontal hydraulic conductivities of the upper and lower aquifers ($K_h$), the vertical leakance between these two layers, and the conductance at the eastern boundary sections. The above-mentioned best-fit results were achieved when the studied area was divided into regions having different hydraulic conductivities and leakances. The $K_h$ values of the upper aquifer varied between 500–550 m/y and that of the lower aquifer varied between 40 and 260 m/y. In both aquifers, $K_h$ increased eastwards where, as noted previously, fracture density becomes larger.

Calibrated vertical leakance between the two sub-aquifers (layers 5 and 6) varied between $9 \times 10^{-2}$ m/y in the Mitzpe Jericho and Herodion areas to $10^{-5}$ m/y in the Ma’ale Adumim area. Near the major springs, the higher leakance was assigned due to the influence of the faulted area, enabling flow to occur from the lower towards the upper aquifer. The division of the area was found to fit the data of the hydraulic connectivity between the two aquifers as observed in boreholes. For example, in the Mitzpe Jericho area, the local faults cause leakance of groundwater from the lower to the upper aquifer, reducing the head difference (Guttman and Rosenthal, 1991). Similarly, in the Herodion area there are faults (Guttman and Gottlieb, 1994), resulting in a small difference in heads between

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the sub-aquifers. In the Ma’ale Adumim area, though, a large head difference between the lower and upper aquifers (Shachnai, 1981) likely results from a low leakance.

Best-fit results exhibit that leakance between the upper and lower sub-aquifers may take place in both directions, depending on the specific head difference. This phenomenon has been observed in wells, but has never been qualitatively or quantitatively explained. Our model has successfully simulated these observations; that is exhibited in two W–E cross-sections (Fig. 8). Both upward and downward flow directions are seen in row 28 (Fig. 8a), while in row 52 (Fig. 8b), a downward flow direction occurs throughout the whole path. Water table elevation in the upper aquifer has a step-like structure on the W–E cross-section (Fig. 8a), because of the intermediate anticline separating between two synclines. At the lower aquifer, on the other hand, groundwater elevation has a gradual gradient throughout the section. Therefore, at the higher western syncline, adjacent to the anticline, groundwater leaks downwards. However, at the lower eastern syncline, adjacent to the anticline, groundwater leaks upwards.

Subtraction of the surface elevation of the base of the upper aquifer from its water table elevation determines its saturated thickness (Fig. 9). Transmissivity values of the upper aquifer were calculated by multiplying the saturated thickness by $K_h$. Comparing these results with transmissivities obtained by pumping tests in wells shows a slight difference (Table 1).
The model-calculated transmisivities were higher than those obtained in wells. This scale-dependence hydraulic conductivity is a well-known phenomenon (Garven, 1994), which results from the larger heterogeneity (stratification, faults and karst systems) occurring at the basin scale compared with the heterogeneity at the well scale.

Finally, four sets of sensitivity analyses were conducted to test the effects on model results of changes in: (a) horizontal hydraulic conductivities of the aquifers, (b) recharge rate (net rainfall infiltration), (c) vertical leakance through the aquitard between the two aquifers, and (d) conductance of the eastern boundary. About 100 numerical runs were conducted to fulfill these analyses. It was found that slight changes in either the aquifer’s horizontal hydraulic conductivities or slight changes in recharge rate affect dramatically the distribution of hydraulic head throughout the area. On the other hand, changes in the aquitard vertical leakance or in the eastern boundary’s conductance do not affect the overall head distribution, but only the relative fraction of discharge at each of the springs. Because our data regarding head measurements in wells are much more accurate compared to spring discharge measurements, we are quite confident regarding the estimations of conductivity and recharge, but less confident regarding the leakance and conductance estimations. It should be noted that sensitivity tests were targeted to examine the influence of changing one parameter at a time. No optimization procedures to balance between changes of several parameters were applied. Obviously, transient modeling is required for better parameter estimations.

4. Discussion and implications

4.1. Structure-dictated flow

The 3D groundwater flow diagram (Fig. 7) exhibits the influence of the geological structure on the flow field. Groundwater flow is diverted northwards and does not follow the general W–E hydraulic gradient. The folded structure creates a ‘river-like’ flow pattern within the upper phreatic aquifer, where groundwater flow is mostly parallel to the synclinal axes and sometimes meanders from one to an adjacent syncline. When water table levels are slightly higher than the adjacent anticline barriers, groundwater
overflows across. Where an anticline axis terminates or exhibits a saddle-shaped structure, the entire ‘subsurface-river’ meanders into the adjacent lower syncline. At the lower confined aquifer, where groundwater elevations are usually much higher than the anticline barriers, groundwater flows mostly eastwards. Yet, groundwater levels in the lower sub-aquifer are commonly lower than the elevation of its exposures along the cliff south of Kane and Samar springs; thus there is no continuous leakage along the cliff. At these locations, groundwater discharge occurs in the subsurface towards the Dead Sea.

4.2. Water balance analysis

Discharge volumes of 34.2, 25.8 and 3.2 MCM/y were calculated to emerge through the Tsukim, Kane-Samar and En-Gedi springs, respectively. Additional 20.6 MCM/y leak below the land surface into the Dead Sea, from which 6.3 MCM/y leak between Tsukim and Kane-Samar springs, and 14.3 MCM/y leak along the entire eastern boundary south of Samar springs (En-Gedi springs emerge much above the coast height). The total calculated discharge is 83.8 MCM/y. One important conclusion is that
the subsurface discharge towards the Dead Sea compared to the discharge in the three major springs is higher than evaluated so far. Sensitivity tests lead to a ratio of 0.35 between subsurface leakage and discharge through all major springs. Although previous estimations of the subsurface leakage were smaller, we argue that the formation of the sinkholes along the Dead Sea shore (Gilat, 1999; Wachs et al., 2000) supports our estimation. The sinkholes are formed due to the ongoing drop of the Dead Sea elevation and the consequent drop of the groundwater/brine interface, which enables subsurface discharge of chemically aggressive fresh groundwater that dissolves some subsurface salt layers.

A better understanding of the flow system within the Judea Group aquifer would be achieved by defining 6 water reservoirs and 4 flux types (Fig. 10). The six reservoirs are the three drainage basins (Tsukim, Kane-Samar and En-Gedi; Fig. 4), each with its upper and lower sub-aquifers. The four flux types are: (i) rainwater recharge by infiltration, (ii) groundwater discharge, either as springs or as subsurface leakage into the Dead Sea, (iii) groundwater leakance between upper and lower aquifers through the separating aquitard, and (iv) groundwater overflow from one to an adjacent drainage basin. The annual fluxes between these reservoirs were calculated based on the best-fit calibration. Most recharge occurs at the upper aquifer (due to its larger exposure area), from which the Tsukim Basin receives the largest amount. Lateral groundwater overflow takes place only from the Tsukim basin to the Kane-Samar basin and from the latter to the En-Gedi basin. The lateral flow at the upper aquifers is, in fact, overflow across the anticlinal barriers, while at the lower aquifers it occurs within a confined aquifer according to the W–E hydraulic gradient. The major groundwater volume flows in the upper aquifer within the synclines towards the springs.

There is a net leakance of groundwater from the upper to the lower sub-aquifers. This is evident not only at the whole basin scale (Fig. 10), but also when examining each cell separately (Fig. 11—the dominant color is blue). There is downward leakance throughout most of the area, with largest rates at the western sides of the structural barriers, but upward groundwater leakance takes place on the eastern sides of the barriers. As mentioned earlier, this phenomenon is seen as well at the cross section (Fig. 8a). Upward leakance takes place as well near the large springs, where groundwater emerges from both sub-aquifers. In fact, about 75% of the upward leakance occurs adjacent to the springs (33 out of the total 46 MCM/y of upward leakance).

The downward flow of 10.3 MCM/y in Tsukim Drainage Basin (Fig. 10) is the net amount; which is equal to the difference between 33.9 and 23.6 MCM/y of downward and upward leakances, respectively. Likewise, in the Kane-Samar Drainage Basin, the net upward leakance of 3.0 MCM/y is the difference between 22.3 and 19.3 MCM/y. However, in the En-Gedi Drainage Basin, there is only downward leakance of 7.8 MCM/y. These flow directions and volumes demonstrate the complicated flow pathways within the aquifer. They also explain why it would be
difficult to analyze the geochemical composition of the upper and lower sub-aquifers, even in case each has a distinct fingerprint. Furthermore, groundwater age determination will be complicated because of the upward and downward leakances.

4.3. The eastern boundary

In the calibration process, we faced a major problem at the northern part of the eastern boundary. During the numerical experiments, we assigned two types of boundaries, either no-flow or conductance, and unfortunately we failed in reproducing the observed data. However, as will be explained below, through these experiments we obtained insight into the flow system, and thereby a successful numerical simulation was achieved; which was later supported by additional, independent field data. As mentioned earlier, the eastern boundary through which discharge takes place, represents the rift faults that place the Dead Sea Group against the Judea Group. Groundwater flow through this boundary depends mainly on the permeability of the Dead Sea Group. The Dead Sea Group, as common rift sediment fill, exhibits inter-fingering between clastic-porous and lacustrine-impermeable rocks, with an eastward increase in the abundance of impermeable strata (Fig. 12). Therefore, the boundary should be defined as no-flow where the sediment fill adjacent to the fault is composed of impermeable rocks. But, where permeable sediments exist at the western side of the fault (as illustrated in Fig. 12), a conductance value, which regulates the discharge rate should be assigned at the boundary.

During simulation experiments we used both, either closed or open boundaries. However, when assigning a no-flow type boundary, meaning that the Dead Sea Group is impermeable, the result was extremely high heads, which do not fit the observed heads at Mitzpe Jericho and Jericho wells. When assigning a high enough conductance so that the heads were reduced and fit the observed ones, the discharge at Tsukim Springs was reduced much below the observed discharge. Our final solution is based on the second option (open boundary), but we assume that after subsurface discharge through this boundary into the Dead Sea Group Aquifer (Fig. 12), groundwater continues to flow southward and emerges at the Tsukim Springs. In other words, fresh groundwater of the Tsukim springs does not emerge only directly from the nearby cliff, but a major fraction originates from the north, flowing southwards, parallel to the faults.

To support this hypothesis, data presented by Shachnai et al. (1983) have been evaluated.
Groundwater elevations were measured in 21 shallow wells penetrating the Dead Sea Group Aquifer between Jericho and the northern Dead Sea shore. The water table exhibits a southward hydraulic gradient, from $K_{289.9}$ m at Jericho to $K_{392.8}$ m at the Dead Sea, along a horizontal distance of 10 km. These elevations probably reflect southward groundwater flow, parallel to the cliff. Moreover, while flowing, groundwater salinity increases, probably due to mixing with the Dead Sea brine.

Finally it should be noted that although our hypothesis explains all observations (well heads at the Judea Group Aquifer, Tsukim Spring discharge, hydraulic gradient within the Dead Sea aquifer etc.), some new questions arise. For example: the positioning of the model’s northern boundary. Even if the constructed boundary is indeed a flow line, groundwater flowing north of this line could enter the Dead Sea Group and flow southwards, adding water to the discharge volume. There are some relatively large springs near Jericho, which could be the outlet to this apparent water access. This remains an open question.

### 4.4. Management

Residents living in the study area, Israelis and Palestinians, have faced water shortage during the last few decades due to overexploitation and degradation of water quality. The 85 MCM/y of fresh groundwater in this area, from which only ca. 15 MCM/y are pumped, are of excellent quality, and could be managed more efficiently if the flow field is better understood. This research enables to draw good qualitative and quantitative options for better management. Obviously, the best pumping areas from the upper aquifer are located within the synclines, where the thickness of the saturated zone is maximal (Fig. 9). The depth to water is an important factor affecting drilling locations. This could be drawn based on the calculated water-table maps (Fig. 6). Salinization processes should be considered as well, especially in the lower sub-aquifer and adjacent to the interface with the Dead Sea brine. This issue was not analyzed in this study.

Exploitation should also be planned according to environmental considerations. In this area, pumping influences spring discharge and thereby the nature reservations in the spring surroundings. The smallest amount of groundwater emerges at the En-Gedi springs, thus they are most sensitive. Pumping from the Tsukim and Kane-Samar Drainage Basins would reduce the discharge rates, but would not cause drying as these are less sensitive. Nevertheless, the numerical solution suggests that there is interaction between the sub-basins, and a large groundwater flux (7.3 MCM/y, Fig. 10) overflows the structural barriers from the Kane-Samar basin towards the En-Gedi basin. This suggests that pumping in the Kane and Samar basins may likely reduce the discharge at En-Gedi springs. These considerations must be kept in mind when decisions on new pumping wells are to be made. In order to examine the quantitative influence of
a specific borehole and pumping volumes, a transient simulation should be conducted.

5. Summary

This work presents a conceptual and numerical analysis of groundwater flow in the thick carbonate Judea Group Aquifer beneath the Judean Desert, Israel. The west–east hydrologic gradient from Judea Mountains to the Dead Sea is very steep; i.e. 800 m head difference over a distance of 25–30 km. However, groundwater flow is not parallel to this general gradient; rather, flow is diverted northward due to the geological folding structure. Therefore, there is no continuous groundwater leakage from the exposed aquifer along the base of the cliffs near the Dead Sea shore. The annual recharge of approximately 85 MCM emerges through three large springs: Tsukim, Kane and Samar; all located in the northern part of the Dead Sea.

In this study, all available geologic and hydrologic data were gathered and processed into a 3D numerical model. The studied area was divided laterally into 3 drainage basins, and each was divided into 2 horizons, upper and lower sub-aquifers, separated by an aquitard. The numerical model was calibrated for natural steady state conditions using the MODFLOW code. The best-fit solution leads to several new insights.

1. The hydraulic properties of the system: the best-fit solution was attained with horizontal hydraulic conductivity values of 500–550 and 40–260 m/y in the upper and lower aquifers, respectively. The vertical hydraulic conductivity of the aquitard between these two aquifers varies between $9 \times 10^{-2}$ and $10^{-5}$ m/y.

2. Groundwater flux between the subsurface drainage basins: the drainage basins are not completely separated; meaning that the structural barriers do not block the eastward flow everywhere throughout the area.

3. Groundwater flux between the sub-aquifer: the numerical model enables, for the first time, to analyze the vertical leakance between the upper and lower sub-aquifers, including its spatial variability. Downward leakance occurs throughout most of the area, but upward leakance takes place adjacent to structural barriers (at their eastern sides) and adjacent to graben faults near spring locations.

4. Discharge of springs compared to subsurface flow to the Dead Sea: subsurface flow from the Judea Group aquifer, through the Dead Sea Group aquifer into the Dead Sea, is apparently larger in volume compared...
to previous estimations. The model suggests about 20 MCM/y of subsurface leakage and 64 MCM/y discharge through the Tsukim, Kane, Samar and En-Gedi Springs.

5. Groundwater outlet location of the Tsukim Springs water: the calibrated model shows that the freshwater source of Tsukim springs is not only directly from the carbonate aquifer adjacent to the springs, but also from the leaks across 10 km-long faults (into the Dead Sea Group Aquifer) that flow southwards in the subsurface towards the emerging location.

6. Practical implications: the calibrated model may help in the future for developing aquifer management schemes, including pumping fresh groundwater for Israeli and Palestinian settlements and conservation of nature reserves.

Acknowledgements

This paper summarizes the MSc thesis of the first author (Laronne Ben-Itzhak, 2003), conducted under the supervision of the second author. This research was supported by grants from the Ring Research Fund at the Hebrew University of Jerusalem and from the Ministry of Environmental Quality (through the Authority for Nature and National Parks Protection). The authors thank Mr Adi Bin-Nun for his help in the GIS analyses; Dr Alon Rimer and Mrs Svetlana Lumelsky for their help in calibrating the computational model; and Dr Yosi Guttman and Mr Nisim Keshet for their helpful remarks. Finally, we would like to thank Prof E. Rosenthal and the second anonymous reviewers for their constructive remarks.

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