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The Many Facets of Israel's Hydrogeology

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About the Editors

Dr. Uri Kafri was born in 1935 in Israel. He received his Ph.D. degree in geology and hydrogeology in 1969 from the Hebrew University in Jerusalem. He is with the Geological Survey of Israel since 1960, serving as a senior geologist and hydrogeologist, and as a director of the Survey between 1979 and 1983. Currently, he is active as an Emeritus in the Geological Survey. Along with his career, he was involved in part-time teaching in the Ben Gurion University in Israel and was involved in various geological and hydrological studies in Israel. His professional activities abroad included hydrogeological surveys and studies in Nepal, Central Africa, South Africa, Tonga, Germany and the USA. He served as a member of board of directors of Earth Science research institutes, as well as a member of several professional committees. He has been serving for a long time in the editorial board of Environmental Earth Sciences.

Prof. Yoseph Yechieli was born in Israel in 1955. He received his B.Sc. and M.Sc. degrees in Geology and Hydrogeology from the Hebrew University in Jerusalem and Ph.D. in hydrogeology and geochemistry of groundwater from the Weizmann Institute of Science. He is a senior researcher at the Geological Survey of Israel and an adjunct professor at Ben Gurion University in Sede Boker since the last 10 years. He is currently the director of the Geological Survey of Israel. He was the president of the Israeli Geological Society in 2006–2007 and chairman of the Israeli Association of Water Resources in 2010–2012. He served as an associate editor of the journals *Groundwater* and *Hydrogeology Journal*. Throughout his career, he has been involved in hydrogeological and geochemical research of coastal aquifers, including the issues of seawater intrusion and dating of groundwater near the Mediterranean Sea and the Dead Sea and in research of sinkholes formation.

Introduction

Uri Kafri and Yoseph Yechieli

This chapter is a concise overview of the main hydrogeological (groundwater) issues of Israel. The reader will find a broad general picture of the hydrogeological setup prior to delving into specific hydrogeological issues that are discussed and detailed in the following chapters.

Israel, as well as the entire region, suffers from a water shortage due to a population growth and an increase in the standard of living that have led to increased water demand. Due to Israel's climate, the groundwater component is the country's major natural water resource.

1 Climate

Israel is located between latitude 30 and 33 in the transition between the southern semiarid and the northern subtropical climatic zones. Thus, the northern part of the country is influenced by a Mediterranean climate and the south by the arid deserts (Diskin 1970). The rainy season extends mainly from October through March, and the rest of the year is dry. The annual average rainfall map (Fig. 1) shows rainfall distribution, which is determined by distance from the Mediterranean Sea, latitude, topography and elevation above or below sea level (Diskin 1970). The total average annual volume of rainfall is close to 8×10^9 cubic meters. Out of this total, some 70% is lost to evapotranspiration, around 5% is drained by runoff and the small remainder is naturally recharged to the groundwater system (Stanhill and Rapaport 1988).

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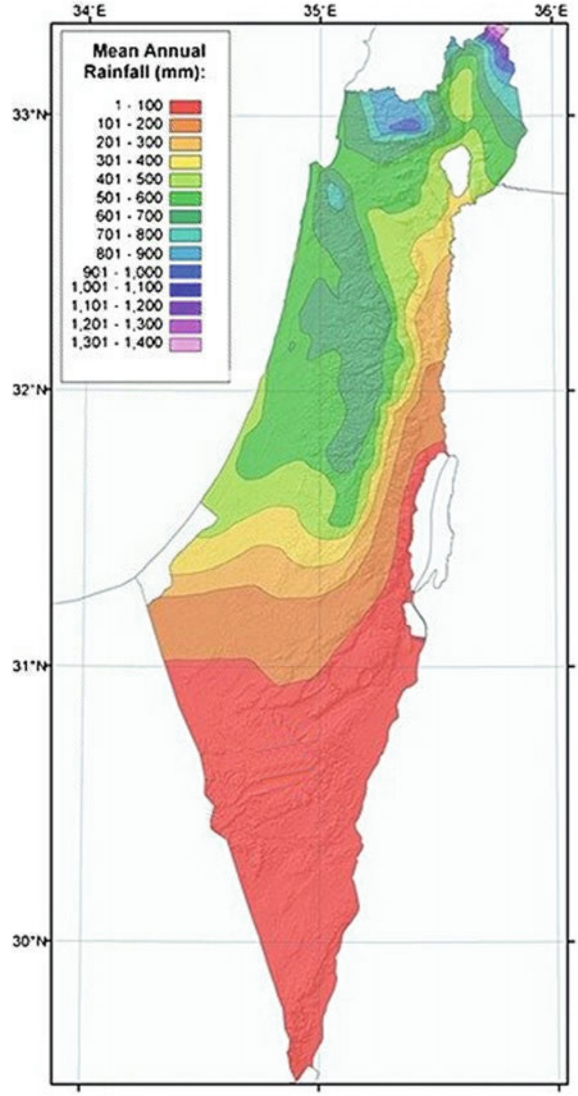

Fig. 1 Annual average rainfall map of Israel (after the Israeli Meteorological Service)

2 Groundwater Base Levels

The country is bounded by three groundwater base levels as follows.

The Mediterranean Sea in the west serves as a base level to regional groundwater flows from the east, from both the mountainous aquifers, consisting mostly of carbonate rocks, and from the coastal detrital aquifer, consisting mostly of calcareous sandstone.

The Gulf of Elat (Aqaba), in the south, which is a tongue of the Red Sea, serves as a base level to convergent flows from two mountainous aquifers: carbonate and detrital. In addition, the southern Arava Valley (part of the Dead Sea Rift, hereafter DSR) detrital graben fill aquifer is drained into The Gulf of Elat.

The DSR in the east serves as an endorheic base level to convergent flows into it from the mountainous aquifers from north, west and east. Also, younger detrital aquifers, as well as basalt aquifers, associated with the DSR and its neighborhood drain into it. The Sea of Galilee and the Dead Sea are part of the discharge zones (detailed in Chapter "The Eastern Dead Sea Rift Continental Groundwater Base Level").

The location of these base levels, coupled with the fact that the Dead Sea is endorheic (terminal) and below sea level (~435 m bsl in 2019) control the interrelationship between them. They also play an important role on the groundwater flow regime as well as on the salinization of the groundwater systems.

3 Groundwater Resources

The main water resources of the country, as detailed by Gvirtzman (2002), among others, are described in brief below. The first three are considered herein as the primary resources, followed by resources of secondary importance. The different hydro-stratigraphic units relevant to the above sources are listed in Table 1. The extent of the exposed lithostratigraphic units that host the above is shown in Fig. 2.

Primary resources:

1. The Judea Group carbonate regional aquifer (JGA) of Cretaceous age is ca 600 m thick. It is exposed to natural recharge mainly along the anticlinorium of the

Table 1 Main lithostratigraphic units in Israel and their hosted main aquifers

Age	Main lithostratigraphic unit	Main lithology	Hydrogeological unit
Neogene to Quaternary	Kurkar Group, Hazeva Formation	Sandstone, gravel	Aquifer
	Cover Basalt	Basalts	Aquifer
Eocene	Avedat Group	Limestones, chalky limestones	Aquifer, aquitard
Early to Upper Cretaceous	Judea Group	Limestones, dolomites	Aquifer
Early Cretaceous	Kurnub Group, Nubian Sandstone	Sandstones	Aquifer
Jurassic	Arad Group	Limestones	Aquifer

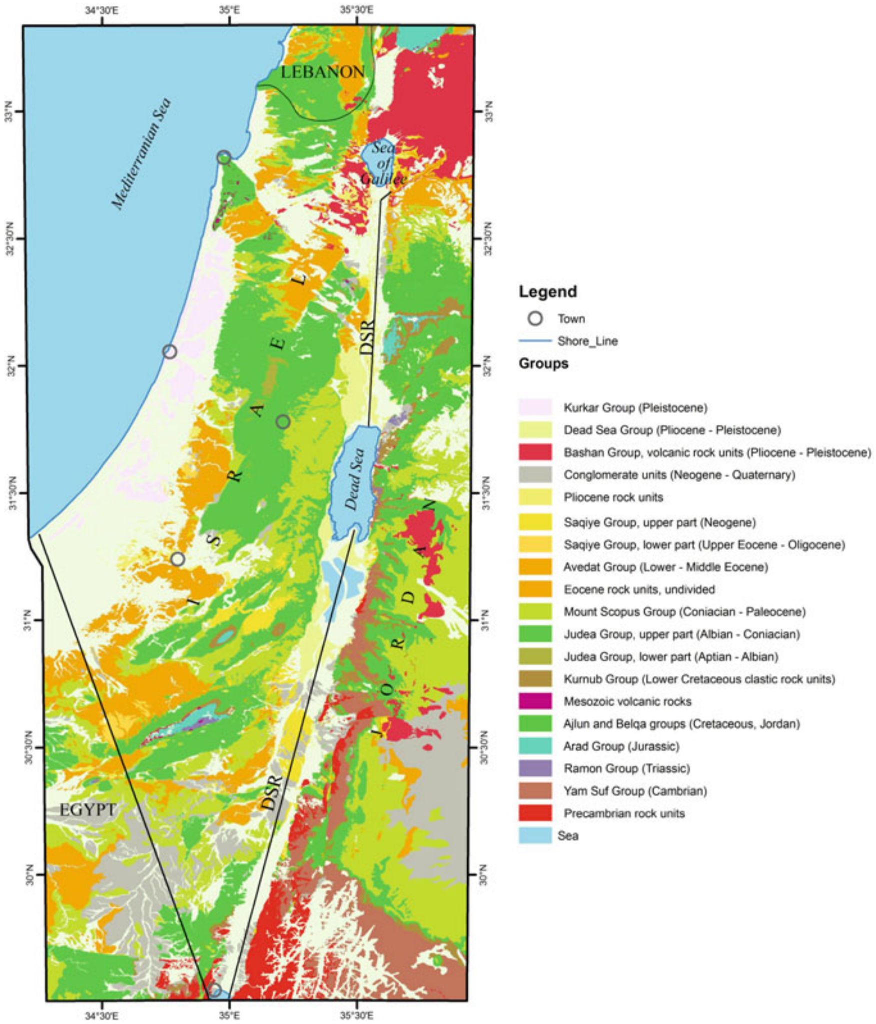

Fig. 2 Extent of the different lithostratigraphic units in Israel (modified after groups map, Geological Survey of Israel 1998)

mountainous regions of Israel from the Galilee in the north, through the Samariya and Judea mountains in the center to the Negev in the south. The aquifer generally dips to the Mediterranean and the DSR base levels and as a result is confined under an upper Cretaceous to Neogene confining sequence. In places, the aquifer is subdivided into lower and upper sub-aquifers. The aquifer drains to both base levels either directly into the sea or through several springs, most of which are presently managed and exploited.

2. The coastal (Mediterranean) aquifer of the Kurkar Group of Pleistocene age extends from the Gaza strip in the south to the Lebanese border in the north. Its thickness varies from a maximum of roughly 160 m near the shore in the south to a few tens of m in the north. The aquifer also wedges out in the eastern foothill regions. The aquifer consists mainly of detrital calcareous sandstones, subdivided by clay and loam confining layers into four known sub-aquifers in its western portion. Its hydrological potential attains on the average around 300 million cubic meters (MCM) per year. Due to a high water demand, the aquifer has been over-exploited in the last decades and as a result subjected in most of its regions to seawater encroachment.
3. The Sea of Galilee has been until recently a major water resource in the northern part of the DSR. It is fed mostly by the Jordan River and its tributaries, namely the Hermon, Dan and Snir streams. The latter drain groundwater that issues via large springs from the Jurassic Arad Group aquifer is exposed and recharged in Mount Hermon. The average yearly inflow to the Sea of Galilee, which is in origin mainly groundwater, is around 500 MCM. The Sea of Galilee is basically a flow-through freshwater lake. However, some salinity is contributed to the lake water from saline springs that issue on the margins of the lake and at its bottom. The lake water was pumped and diverted via a major national conduit system to the more southern parts of the country at an annual amount of a several hundred MCM.

Secondary resources:

1. The Kurnub Group, Nubian Sandstone aquifer of Early Cretaceous age, is known from the subsurface of the southern arid part of the country. Most of its intake area is outside Israel in the Sinai Peninsula. Due to the present-day prevailing arid climate, it was found that most of its water content is paleo groundwater, recharged in the past during more humid climates. The aquifer drains to the Dead Sea and the Red Sea, as well as to the Gulf of Suez in Egypt.
2. The Avedat Group aquitard–aquifer system of Eocene age consists mainly of chalky limestone and chert horizons that constitute an aquitard over most of the country. In certain areas, due to facies changes, this unit passes laterally into a reefal and jointed limestone sequence of a high permeability, essentially forming an aquifer. The Avedat Group aquifer is known mostly from the northern and eastern parts of the country and close to the DSR. The aquifer is perched above the Senonian aquicludal sequence, whereby it is being drained by medium flow size perched springs. Elsewhere, the Avedat Group aquitard is also perched, being drained by several small flow size springs.
3. The basalt aquifers of Neogene to Quaternary age are known in the northeastern part of the country and the Golan Heights close to the DSR. They consist mainly of basalts and agglomerates and are drained by several perched springs. The water contribution of these aquifers to the northern part of the DSR amounts to several tens of MCM, annually.

4. The DSR graben fill aquifers of the Dead Sea Group include the detrital, coarse clastic and sandy aquifers aligned along and adjacent to the DSR. Among these is the Neogene Hazeva sandy aquifer in the south and the Quaternary alluvial, mostly gravel aquifers that were formed as alluvial fans along the DSR, mainly in its southern portion, the Arava Valley. Due to the arid climate that prevails in the south, these aquifers are recharged mainly laterally from the mountainous aquifers on both sides of the DSR as well as by downward percolating seasonal flows along streams that drain to the DSR.

4 Salinization and Pollution of the Groundwater System

The natural salinization processes of the different freshwater aquifers in Israel are controlled mainly by its bordering saline base levels. The western Mediterranean and the southern Gulf of Elat marine base levels contribute salinity to their adjoined coastal aquifers, whereby the latter are encroached by seawater. In addition, in places where the JGA is adjacent and hydraulically connected to the Mediterranean base level, it is also encroached upon by seawater.

The DSR base level in the east, however, occupies concentrated brines, since it was intruded in the past by Mediterranean seawater due to the elevation difference between both base levels. Due to the endorheic nature of the DSR, concentrated brines were and are formed which are encroached laterally in the neighboring mountainous and graben fill aquifers. All the described salinization processes are enhanced by the exploitation or over-exploitation of the relevant aquifer systems.

In addition to the above, some of the shallow exposed aquifers are subjected to anthropogenic salinization and contamination processes. These include domestic, industrial and agricultural pollution.

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The Yarkon-Taninim Basin—An Example of a Major Carbonate Aquifers in Israel

Joseph Guttman

1 Background and Purpose of the Article

Carbonate aquifers constitute a considerable portion of the sedimentary sequence in Israel. Among these, the main aquifers are the Jurassic, the Cretaceous and the Eocene aquifers. Their functioning as potential active freshwater aquifers depends on their exploitation depth or in addition on their exposures to natural recharge through precipitation. Regarding the latter, it depends also on whether their recharge area is located in an arid area or a humid one. In the case of a humid regime, the amount of natural recharge to the aquifers depends also on the altitude of their recharge areas which affects the amount of precipitation. In addition, those aquifers do not play a role as freshwater aquifers where and when they host, or are intruded by saline or hypersaline water sources.

The main and most important carbonate aquifers in Israel are as follows.

1.1 The Jurassic Arad Group Aquifer

This aquifer is a deep-seated aquifer found over almost the entire country, which consists mostly of limestones that are partly karstic. The aquifer contains mostly concentrated brines. Only in the northeastern part of the country, in Mount Hermon, the aquifer, some 2000 m thick, was uplifted to elevations up to close to 3 km above sea level. As a result, the aquifer through its recharge area is exposed to considerable natural recharge via rainfall and snowmelt (i.e., Gila'd and Bonne 1990). The upper sequence of this freshwater aquifer feeds the main three Hermon, Dan and Snir springs and in turn the tributaries of the Jordan River at an average annual amount

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of some 500 million cubic meters (MCM). The latter flow downstream to the Sea of Galilee that serves as the biggest natural water reservoir in Israel. The lower part of this aquifer is assumed to be flowing to deep outlets in Syria, Northern Israel and Lebanon (Burg 2011; Guttman et al. 2012, 2017; Babad 2018).

1.2 The Eocene Avedat Group Aquifer or Aquitard

This hydrogeological unit is of secondary importance regarding its groundwater potential. It extends along the western foothills of the central mountain crest of Israel and close to the margins of the Dead Sea Rift system in the east, as well as in the northern Negev in the south. The aquifer is missing in the central mountain crest of the country. The Avedat Group exhibits lithologically, in general, two lithological facies: (a) chalk and chalky limestone facies throughout most of its occurrences in the west, and thus, is regarded as an aquitard due to its relatively poor hydrological properties. It is, thus, regarded as of secondary importance. (b) a limestone facies, reefal in places, mostly in the eastern part of the country, and considerably jointed, exhibiting a rather high hydrological conductivity and regarded as a good aquifer. However, due to its limited exposed recharge area, mostly close to the Dead Sea Rift in the east and northeastern parts of the country, it is also secondary of importance. The same goes for the northern Negev Avedat Group aquifer due to the arid regime that prevails there.

1.3 The Judea Group Carbonate Aquifer

The Judea Group carbonate aquifer of late Cretaceous age is the most important regional aquifer in Israel. The aquifer consists mainly of dolomites and limestones, in places interbedded by chert-bearing chalk and marl units that subdivide the sequence to sub-aquifers. The total thickness of the aquifer is around 700–800 m all over most of the country except for its southernmost parts where the thickness is reduced approaching the Arabo-Nubian massive. The aquifer extends over most of the country but it is being exposed mainly in its north–south directed-central mountain crest from the Negev in the southward and northward along the Judea and Samaria Mountains as well as in Mount Carmel and in the Galilee Mountains. Its exposure, and being subjected to natural recharge, is related to the uplift of the mountainous region along the Syrian Arc since the Senonian (i.e., Shahar 1994) forming northeast–southwest-directed synclines and anticlines an accompanied by the erosion of the overlying formations. Two later uplift phases, two of which predated the formation of the Dead Sea Rift system in the east (Bar et al. 2016), enhanced the process of exposure. As a result, the Judea Group aquifer vast exposures serve as recharge areas to natural recharge to the aquifer that except of the arid south, serves as the main groundwater reservoir of the country. The aquifer was naturally drained by several springs that are currently managed and artificially exploited by a vast network of exploitation wells. The general flow pattern of groundwater from the elevated recharge areas is being, basically controlled by the existence and location of the western, Mediterranean and the eastern Dead Sea Rift base levels. In addition, it is also influenced by the tectonic system, which includes faults, grabens, horsts, and secondary structures of anticlines and synclines. The tectonic system also determines the location of the natural outlets of the aquifer and affects the flow path and the flow gradients.

The structural axis of the mountain crest, in general, dictates the location of the regional groundwater divide between the so-called Western Aquifer which drains to the Mediterranean base level and the "Eastern Aquifer""which drains to the Dead Sea Rift base level. The "Western Aquifer" in Western Galilee and in the central Judea and Samaria Mountains is the main fresh groundwater resources of Israel.

The Judea Group aquifer was intruded from the west since the Neogene and later on during Pleistocene transgressions by seawater. During subsequent regression periods, the system was flushed by naturally recharged meteoric water. The meteoric water replaced the salt water in the carbonate formation. Nevertheless, there are few areas in the western foothills and close to the sea where the aquifer still contains unflushed or currently intruded seawater. Similarly, the Judea Group aquifer was intruded in the past and is still intruded by concentrated brines that occupy the Dead Sea Rift base level. Thus, proper management of water resources in each of the aquifer basins is based on a deep understanding of the geological, hydrological and salinization hazards that may be caused by different operating regimes.

This chapter focuses on part of the main carbonate aquifer of Israel, namely the Western Mountain Basin of the central mountain ridge, named as the "Yarkon-Taninin Basin," which constitutes the major part of the Judea Group aquifer of the western basin. It was chosen, herein, as an example for the others carbonate aquifers in Israel due to its importance to the water supply system, to its hydrogeological complexity and to the considerable abundance of geological and hydrological data.

The "Yarkon-Taninin Basin" is an important component of the Israel National Water supply system, and the pumping from this basin is influenced by its hydrological conditions as well as by the abstraction from the other water supply sources of the Israel National Water system (desalinated seawater, the Coastal Aquifer and Lake Kinneret-Sea of Galilee).

2 Hydrogeology of the Yarkon-Taninim Basin

This chapter summarizes the conceptual hydroglogical model of the "Yarkon-Taninin Basin" and its groundwater management policy of this basin. It is a unique example how to manage a large carbonate and karstic aquifer by combining deep understanding of the geology, hydrology and geochemistry of water sources with local and regional water supply needs.

A schematic geological cross section (Fig. 1) across the central mountain region in Israel exhibits the western and eastern basins and the anticlinal crest in between.

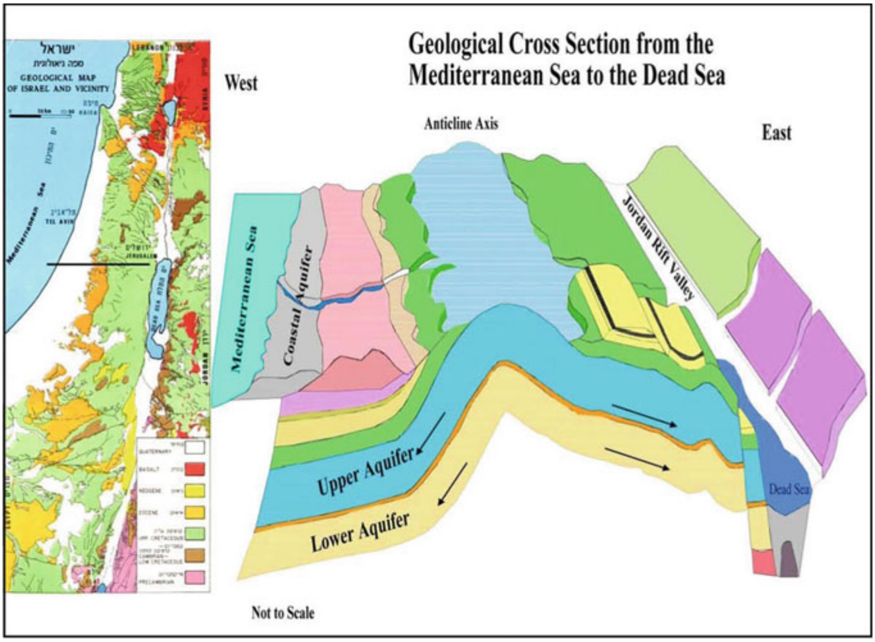

Fig. 1 Schematic geological cross section through the central mountain region in Israel showing the western and eastern basins and the anticlinal crest

The groundwater divide that generally coincides with the crest of the anticlinal axis divides the system to the separate western and eastern hydrological basins.

The Yarkon-Taninim (Western Mountain Aquifer) Basin extends over the western flank of the central mountain ridge of Israel. This aquifer is one of the three largest water reservoirs in Israel and has the highest water quality.

The boundaries of the basin are from Nitzana in the south to Yoqne'am area in the north and from the coastal area in the west to the mountain crest in the east (Fig. 2). The size of the basin is around 10,000 km^2.

The hydrogeology of the basin was studied and described in several articles (i.e., Weinberger et al. 1994) and reports. A summary of the latter is found in Dafny (2009) and Dafny et al. (2010). Therefore, only elements that are important for the understanding of the general hydrological conceptual model and to the management of this aquifer are mentioned herein.

According to the above-mentioned studies, the aquifer consists mainly of limestone and dolomite layers with interbedded layers of chalk, marl and clay. The total thickness of the aquifer varies from 800 m in the northern and central part, to about 500–550 m in the southern part of the basin. The aquifer is divided into three hydro-stratigraphic units:

Lower unit (KUJ1), consisting of dolomite and limestone, partly karstic of high permeability. In its southern part, it is also interbedded by thin layers of shale. The unit is characterized by a moderate to high hydraulic conductivity.

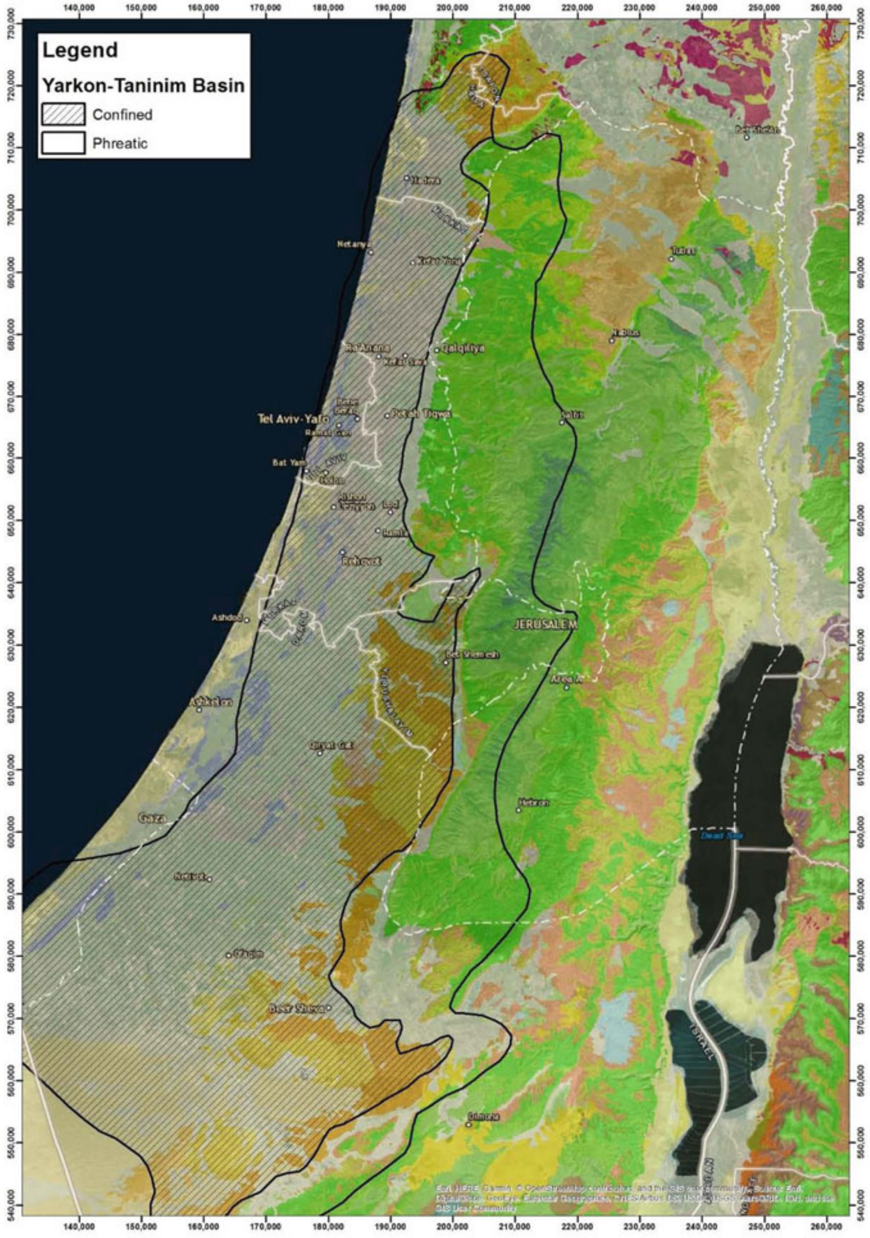

Fig. 2 Boundaries of the "Yarkon-Taninim Basin"

Middle unit (KUJ2), consisting of alternations of chalk, limestone and marl and sometimes dolomite. The unit is characterized by a low to moderate conductivity. In most of the basin, it is practically an aquiclude that separates between the lower unit and the upper one.

Upper unit (KUJ3, KUJ4), consisting of dolomite and limestone with abundant karst phenomena and thus characterized by a high conductivity.

Drilling results accompanied by analyses of geophysical logs from many wells and television profiles in some of them, show that the aquifer, whose thickness reaches several hundred meters, contains a large number of joints, cracks and karst cavities. All the above revealed karstic cavities of several meters height together with a denser network of joints and cracks.

The locations of the cracks and the significant karstic caves vary between adjacent wells and along the aquifer section. It was found, as expected, that there is a direct relationship between the quantity and the size of the cracks and the karstic caverns along specific well profiles and the hydraulic properties (transmissivity and specific discharge) obtained from their pumping tests. Wells typical of a dense system of cracks and karstic caves indeed reveal a relatively high hourly yield with a small drawdown and a high transmissivity at the range of thousands to tens of thousands of m^2/day and vice versa (Table 1 and Fig. 3).

Yechieli et al. (2009) claimed that in some regions, the lower sub-aquifer in this basin is less conductive than the upper one as was simulated in their model. Their results revealed, in general, a higher specific discharge and transmissivity values typical to the upper sub-aquifer as compared to the lower one.

As mentioned before, the transmissivity value and the specific discharge in each well are combination result of the aquifer properties (the amount and the dimension of the karst caves and cracks and the thickness of saturated layers) together with the well construction (diameter, length of the open aquifer section and the percentage of the screen open area) in each well. It is usually difficult to determine based on joints and caverns abundance in each well, its preferred conductive portion of the sequence. Therefore, as a common rule in Israel, the length of the production section in each well (open screen) in carbonate aquifers is planned to be chosen between 100–200 m.

The distribution of the transmissivity values from selected wells in the aquifer area, based on the data of Table 1, is exhibited in Fig. 4. It is evident that the transmissivities are, in general, lower at the mountainous areas in the east and are considerably higher toward the foothills region in the west. In some cases, local high transmissivity values are found also in the high elevated areas. The same transmissivity distribution was modeled and described by Yechieli et al. (2009).

Based on the hydro-stratigraphic classification, the water levels and the water quality, the entire aquifer, as mentioned before, are sub-divided into two sub-aquifers, namely an upper sub-aquifer and a lower one, whereby the middle unit separates between the two sub-aquifers (Guttman 1991, 1998, 2002). However, based on water balance considerations, it is quite clear that the middle unit is acting in several parts of the basin as an aquiferous unit that forms a hydraulic connection between the two sub-aquifers (Guttman 1988).

Table 1 Hydrological data from pumping tests in selected wells

Name	Sub-aquifer	Q (max) (m^3/h)	Drawdown (m')	Specific discharge (m^3/h/m′)	Transmissivity (m^2/day)
M-Sade 1a	Upper	324	8	40.5	11,535
Omer 1	Upper	210	2.4	87.5	15,400
B-Sheva 1a	Upper	269	1.1	244.5	
Nechusha 1a	Upper	720	11	65	2100
Ein Karem 12	Lower	58	95.5	0.61	9.1
Ein Karem 9	Lower	350	3.75	96	6160
Ein Karem 6	Lower	84	54.8	1.5	105.6
Eshtahol 5	Lower	405	11.3	35.8	4245
Eshtahol 8	Lower	665	8.67	76.7	17,150
Achisemech 1	Lower	1148	5.5	215	11,842
Lod 32	Upper	1718	4.77	360.2	492,500
Lod 17a	Upper	648	0.22	2945	
Yarkon 9	Upper	1056	29.2	36.2	18,586
R. Haayin 10	Upper	1825	7.19	253.8	88,815
R. Haayin 12	Lower	1501	11.09	135.3	21,821
Neve Yarak 2	Upper	2458	12.75	192.8	107,665
S-Deromi 103	Upper	2370	19.05	124.4	
S-Zefoni 203	Upper	2028	11.34	178.8	425,300
Kakun 5	Upper	280	1	280	5500
K-Shomrom 1	Lower	195	31.7	6.15	238
Ariel 1a	Lower	215	79.6	2.7	80
Tut 4	Upper	638	8	80	12,848
S-Menashe 1	Upper	1300	23.5	55.2	10,000
Maanit 5	Upper	1440	3.9	370	

Source Mekorot Water Company archive

When dividing the aquifer's outcrops and recharge areas according to their belonging to the lower or upper sub-aquifers, it turns out that most of the natural recharge (about 70%) finds its way to the lower sub-aquifer. It takes place in the mountainous region through the exposures of the lower sub-aquifer as well as through the exposures of both saturated and unsaturated upper sub-aquifer via the connection areas (Fig. 5). At the same time, most of the pumping is carried out through wells that penetrated the upper sub-aquifer. Since the considerable exploitation of the upper sub-aquifer is not expressed by a parallel drop of the water level, it demands a compensation mechanism which contributes groundwater from the lower, into the upper sub-aquifer at the rate of at least tens of million cubic meters (MCM) in order to balance the pumping and springs flow of the upper sub-aquifer.

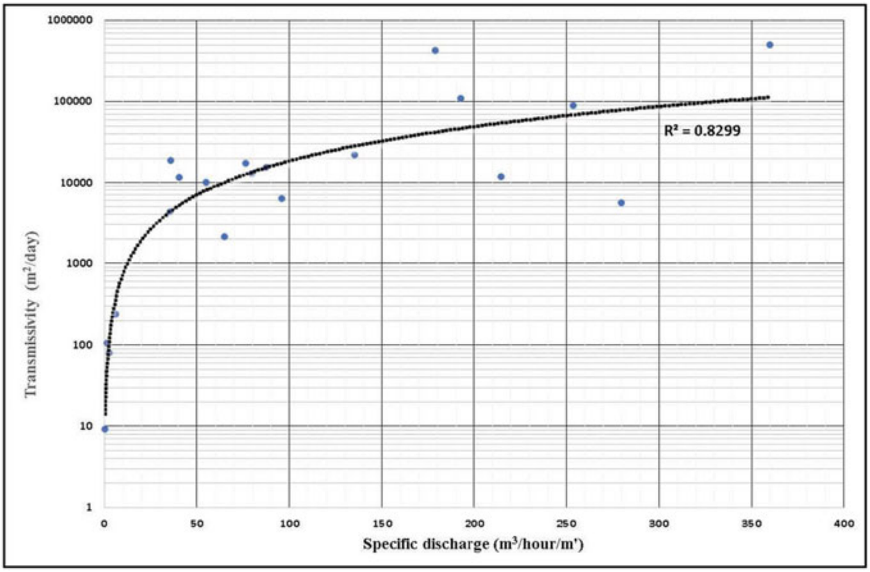

Fig. 3 Correlation between the specific discharge and transmissivity

The massive amount of water that potentially flows from the lower sub-aquifer into the upper one requires large connection areas. The delineation of the connection areas in the entire basin is essential to any 3D flow model that attempts to simulate the water passage from the lower to the upper sub-aquifer (Guttman 1988), and the results (Fig. 5) are valid until today.

According to the above described setup, and due to regulatory reasons aimed to maintain protection zones, the current policy is to drill the new wells west to the foothill, in the phreatic part of the aquifer, mainly into the deep sections of the upper sub-aquifer and\ or to the lower sub-aquifer.

The phreatic region extends from the groundwater divide in the east to about 1–3 km west of the foothills region (Figs. 4 and 5). More to the west, the aquifer is overlain by Senonian confining layers, forming confined conditions, whereby the water level is above the top of the aquifer. Most of the pumping takes place through wells located near the foothill and a few kilometers west of the confining line, which delimits the passage from phreatic to confined conditions.

The first wells were drilled close to the foothills as early as in the 1940s. Accelerated activity of drilling and development of the pumping capability from the aquifer had taken place during the fifties and sixties of the twentieth century. The massive pumping in the central part of the basin and close to the Yarkon springs dried up these springs around the mid-sixties.

Most of the wells that were drilled 50–60 years ago penetrated only a few tens meters into the upper sub-aquifer. Most of those oldest wells were drilled in percussion and in old rotary methods. In those wells, the uppermost unsaturated zone, up to

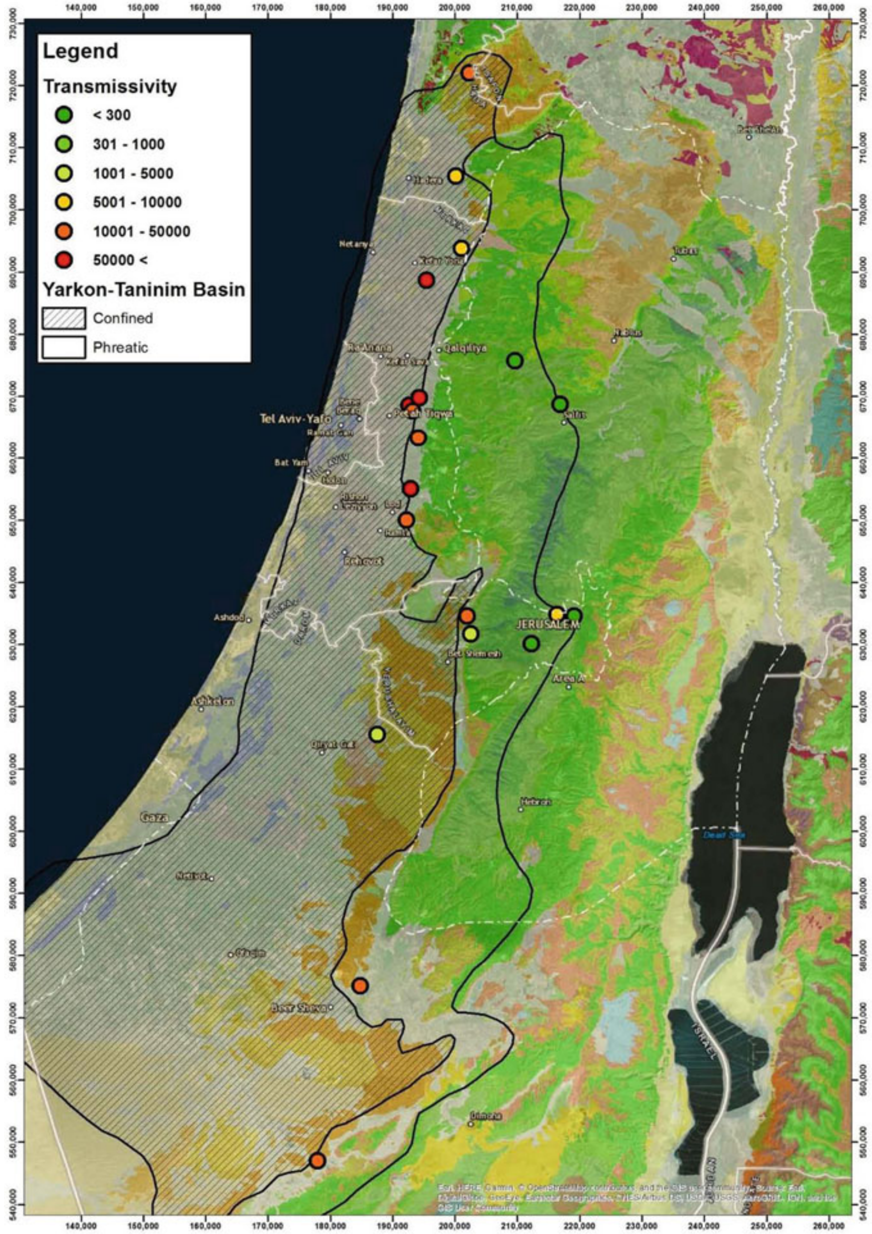

Fig. 4 Transmissivity values in the “Yarkon-Taninim Basin” (based on data in Table 1)

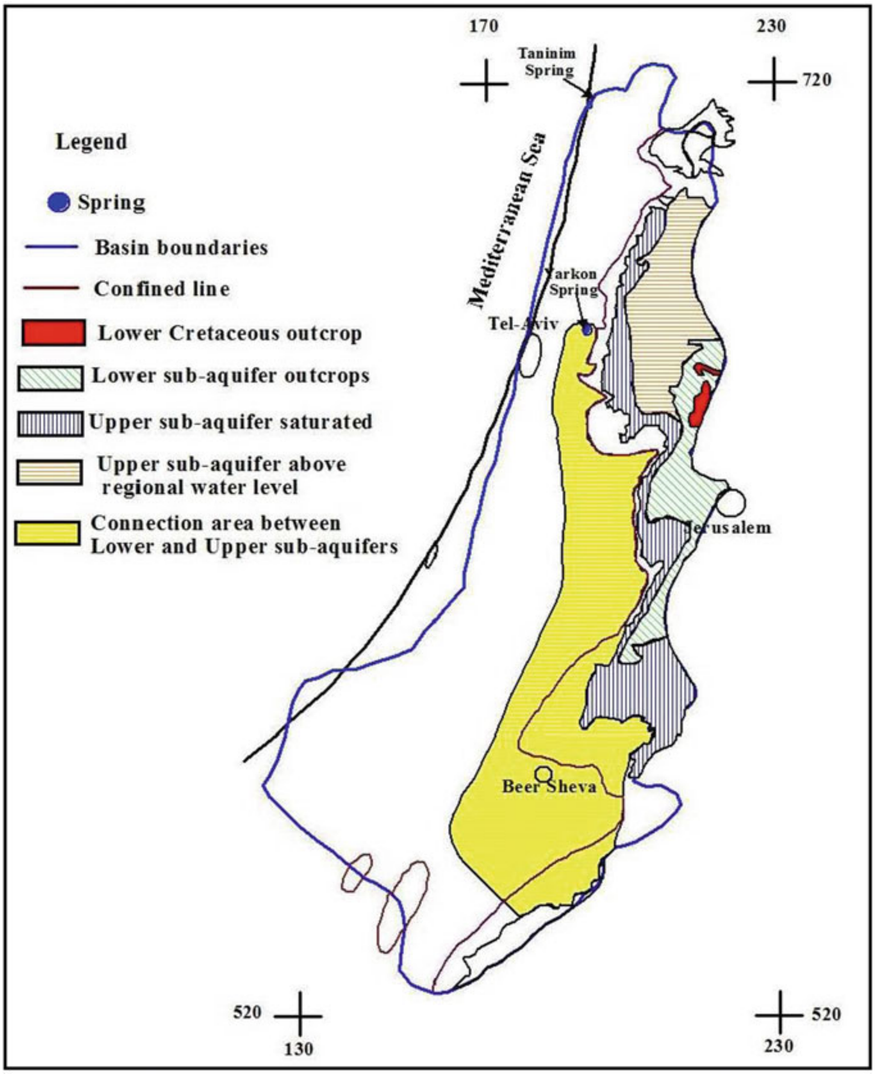

Fig. 5 Location of the "connection areas", after Guttman (1988)

few meters beneath the static water level, was cased by steel casing without cementation and proper isolation of the aquifer from the surface. Some of the oldest wells are, thus, not properly protected from surficial potential contamination. However, contamination events, resulting from leaking of pollutants from the surface, are found to be quite random and explained by the high hydraulic conductivity of the aquifer, and the resultant rapid dilution of the contaminants.

Most of the natural recharge to the aquifers occurs in the mountainous area. The water levels along the high mountain ridge range from 250 m asl, in the Ariel area, to 400–450 m asl in the Ein Karem well field near Jerusalem. Near the foothills, in the west, water level elevation levels are currently between 10 and 15 m asl.

The groundwater flow is from the mountainous area downslope, being controlled by the major geological structures, bypassing the structural obstacles. The water level differences between the mountainous area and the foothills area are some 250–450 m, over a distance of 15–20 km only. In order to maintain the higher water table in the mountainous area and to account for such a steep gradient, it is required to have in between some low hydraulic conductivity strips that act as a hydrological barrier. The location of few potential hydrological barriers is known, based on geology and drilling results. Still, there are large areas in the high mountainous area, where water level data and the locations of the hydraulic parameters are scarce or nonexistent. In this regard, Meiri and Guttman (1984) and Yechieli et al. (2007) have modeled and delimited such a low conductive "barrier" between the Ein Karem well field (close to Jerusalem) and the foothills, which coincides with the western regional steep flexure of the anticlines structure. Across this "barrier," indeed, the water level drops from around 300 m to 15 m asl in the foothill region along a few kilometers distance, exhibiting a very steep groundwater flow gradient.

Upon reaching the foothills and the confined part of the basin, the westward groundwater flow paths are diverted, flowing northward to the natural outlets of the Yarkon springs in the central part and the Taninim springs in the northern part of the basin, as shown in Fig. 6 (Dafny 2009; Dafny et al. 2010).

From the foothills region, to the west and farther to the north, the water level in the phreatic and in the confined parts exhibits a very mild gradient. The drop of 3–5 m over about 150 km is indicative of a very high transmissivity (Fig. 4). In the confined part of the system, the storativity, as expected, is very small, typical to confined conditions. The natural outlets prior to the exploitation of the aquifer were mainly the Yarkon and Taninim springs (Fig. 5). The Yarkon springs in the center of the basin yielded an estimated yearly flow between 220 and 240 MCM/year, and the Taninim springs in the northwestern margin of the basin yielded a yearly discharge around 110 MCM/year.

The Yarkon springs are in practice overflow springs, which resemble an upper drainage tank, sensitive to changes in its water head. In the 1960s, due to the massive pumping and continuous droughts, the water level in the aquifer declined beneath elevation of the spring's outlet and the springs flow ceased. The flow returned after the extreme rainy winter of 1991/92, when the water levels in the entire basin raised by more than 10 m within 3 months.

The Taninim springs, located on the northwestern edge of the basin, serve as the lower outlet of the aquifer. Despite the intensive pumping upstream, they are still flowing, but with a very low discharge.

The forcing head of the Taninim springs was determined during the calibration of several models (Guttman and Zukerman 1995; Guttman and Zeitoun 1996) at an elevation height of 3.6-4.0 m asl. The water level in the nearby pumping fields located some 7–10 km from the springs (Pardes Hana area), vary between 9 and 14 m asl, depending on the natural recharge and the pumping regime. Figure 7 shows the water level in Karkur Pardes Hana well fields and the parallel Taninim springs discharge.

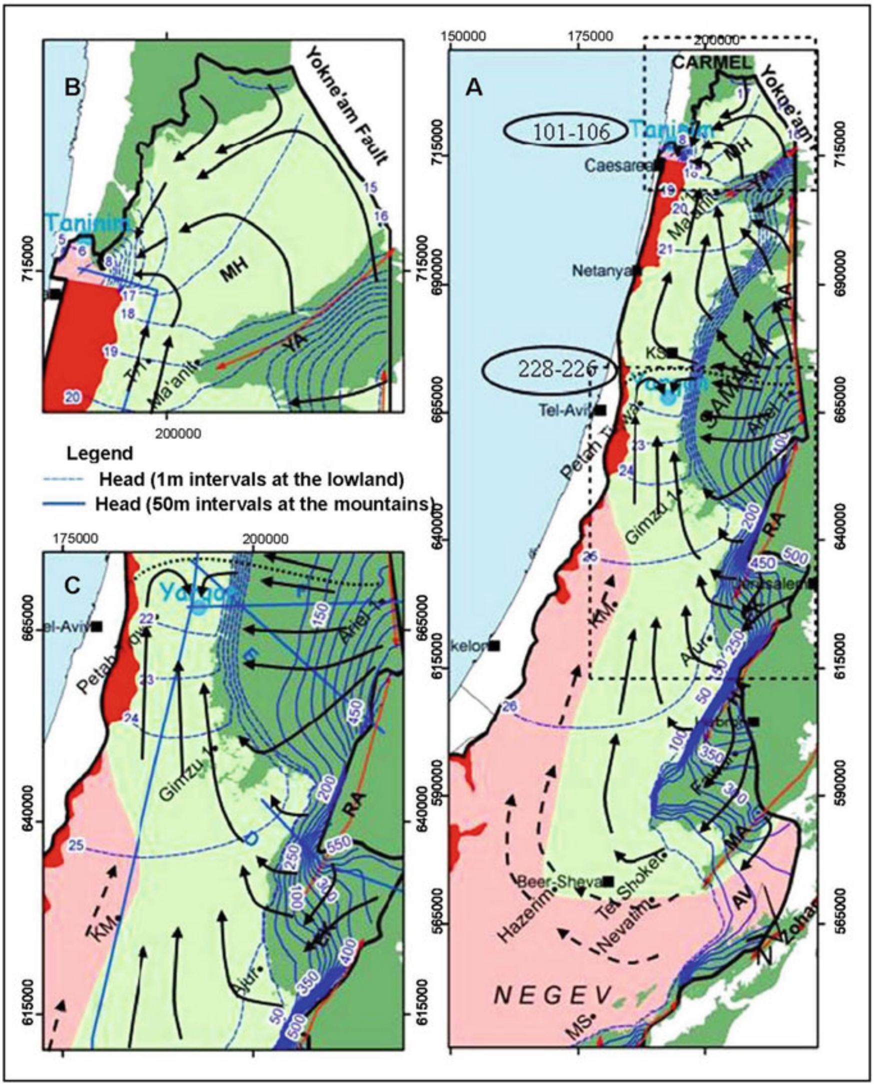

Fig. 6 Regional flow path pattern (used by permission of Elsevier from Dafny et al. 2010, J Hydrol 389:260–275, Figs. 1, 5)

The discharge of the Taninim springs will assumingly continue to drop but will not be completely dry up, like the case of the Yarkon springs.

The average calculated annual recharge into the aquifer for the period 1952–2017 is 346 MCM, whereby the average for 1995–2017 is only 288 MCM (Fig. 8). The reduction of the average annual recharge during the latter period is due to several cycles of dry years. The standard deviation is about 30% and the drop is related to

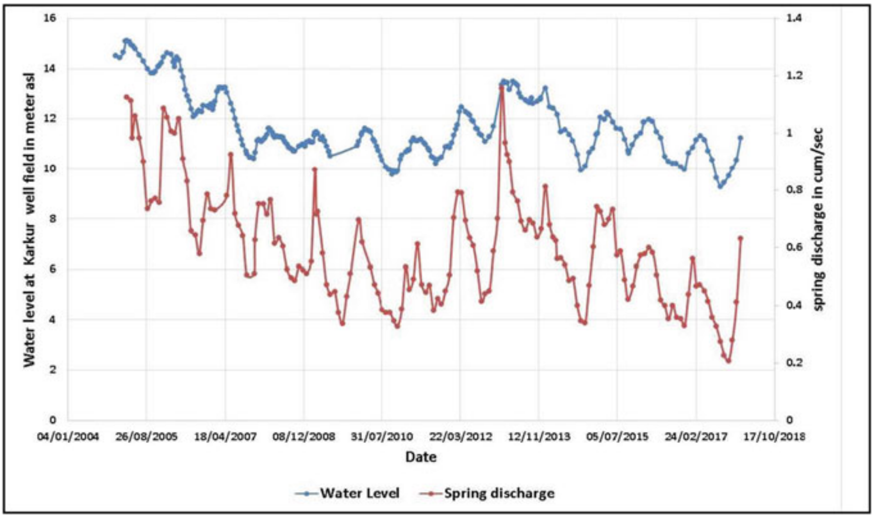

Fig. 7 Water level in the Karkur-Pardes Hana well field and the Taninim spring discharge

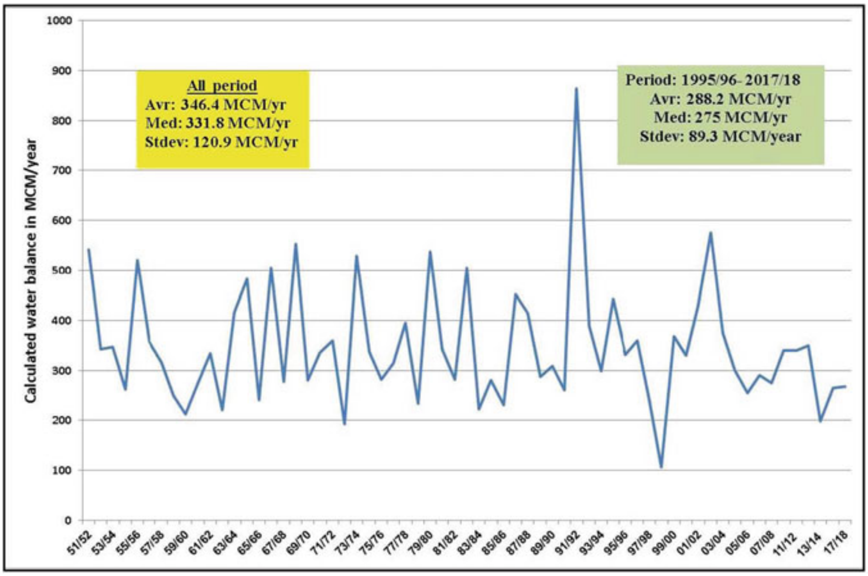

Fig. 8 Calculated natural recharge (Guttman and Zukerman 1995; Guttman, personal calculation)

the effects of climate change and changes in the distribution and in the intensity of rainfall during winter.

The considerable differences in the rainfall, both seasonal and annual, over the recharge areas, also result in differences in the natural recharge between the northern and southern recharge areas. Most of the recharge (90%) occurs in the central and northern parts of the basin. The southern part (Hebron region) contributes only some 10% to the overall natural recharge.

The flow pattern from the recharge area downstream is via several individual paths which also affects the chemical water composition and its quality. The water at the mountainous area is characterized by relatively low salinity, low temperature and "young" age (Guttman 1980; Kroitoru 1987). Upon reaching the foothill and the confined part of the basin, the flow paths are diverted clockwise (Fig. 6), flowing northward through a longer travel time, accompanied by aging of the water along the flow path down-gradient from the recharge areas to the northern Taninim springs outlet. Since the production section in the pumping wells is long (100–200 m), practically, the water composition in each pumping well is an average of the contributions of the aquiferous horizons along the production section.

The aquifer is acting like a huge reservoir. The water level gradient is about 5 m over approximately 150 km. The high transmissivity of the aquifer together with the gentle gradient allows the stakeholder to shift the pumping from one part of the basin to another, by using the aquifer storage as an underground conduit.

The high transmissivities together with the gentle gradients all over the western part of the basin result in similar and regional groundwater level fluctuations as an expression of the pumping in the entire basin (Fig. 12). Practically, it is impossible to halt the pumping from tens of wells for water level measurements. Therefore, the measurements are being carried out also when some of the nearby pumping wells are pumping, namely that the measurements are at a pseudo-dynamic condition. Thus, any changes of the pumping pattern in the nearest pumping wells adjacent to the observation well are immediately been expressed by temporal changes of the water level by few tenth of centimeters. Due to the gentle gradient, changes of several tens of centimeters are significant and can create errors when calibrating a flow model and determining criteria for operating the aquifer.

Several deep monitoring wells were drilled along the western boundary of the basin, located in a syncline west of the pumping well fields, as can be seen in the schematic geological section (Fig. 9).

The monitoring wells were drilled to depths between 1000 and 1400 meters reaching a saline water body that underlies the upper freshwater one. The chlorinity of the saline water was found to be between 17,000 and 20,000 mg/lit. Based on chemical and isotopical considerations, the saline water is interpreted as ancient seawater that had penetrated the aquifer and remained stored in the deep western syncline (Kafri and Arad 1979; Guttman 1980; Guttman et al. 1988; Paster et al. 2005; Burg and Talhami 2014).

The Israel Hydrology Service (IHS) is continuously monitoring the level of the interface between the freshwater and the saline water that is located beneath the