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Cross-formational rising groundwater at an artesian karstic basin: the Ayalon Saline Anomaly, Israel

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Abstract

It is proposed that a geothermal artesian karstic system at the central part of the Yarkon–Taninim aquifer creates the 'Ayalon Saline Anomaly' (ASA), whose mechanism has been under debate for several decades. A 4-year-long detailed groundwater monitoring was carried out at 68 new shallow boreholes in the Ayalon region, accompanied by a comprehensive survey of karstic voids. Results indicate the rising of warm-brackish groundwater through highly permeable swarms of karstic shafts, serving as an outflow of the artesian geothermal system. The ASA area contains 'hot spots', where groundwater contrasts with 'normal' water hundreds of meters away. The ASA temperature reaches 30 °C (∼5 °C warmer than its surroundings), chloride concentration reaches 528 mg/l (50–100 mg/l in the surrounding), H_2S concentration reaches 5.6 mg/l (zero all around) and pH value is 7.0 (compared with 7.8 around). Subsequently, the hydrothermal water flows laterally of at the watertable horizon through horizontal conduits, mixing with 'normal' fresh water which had circulated at shallow depth. Following rainy seasons, maximal watertable rise is observed in the ASA compared to its surroundings. Regional hydrogeology considerations suggest that the replenishment area for the ASA water is at the Samaria Mountains, east of the ASA. The water circulates to a great depth while flowing westward, and a cross-formational upward flow is then favored close the upper sub-aquifer's confinement border.
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Keywords: Groundwater; Rising water; H_2S; Confined karst; Maze caves; Yarkon–Taninim aquifer

1. Introduction

The Yarkon–Taninim aquifer (Fig. 1), the western part of Israel's Judea Group aquifer, is the largest source of fresh groundwater in Israel, supplying an annual average of 360 million cubic meters. Today, this aquifer is endangered due to intensive pumping. The replenishment zone of the aquifer extends along the western slopes of Judea and Samaria Mountains, while most pumping wells spread along the western foothills of the Shefela region, where the aquifer is commonly confined.

In this study, we suggest that a discharge zone of geothermal artesian karstic system exists at the central part of the Shefela region within the Yarkon–Taninim

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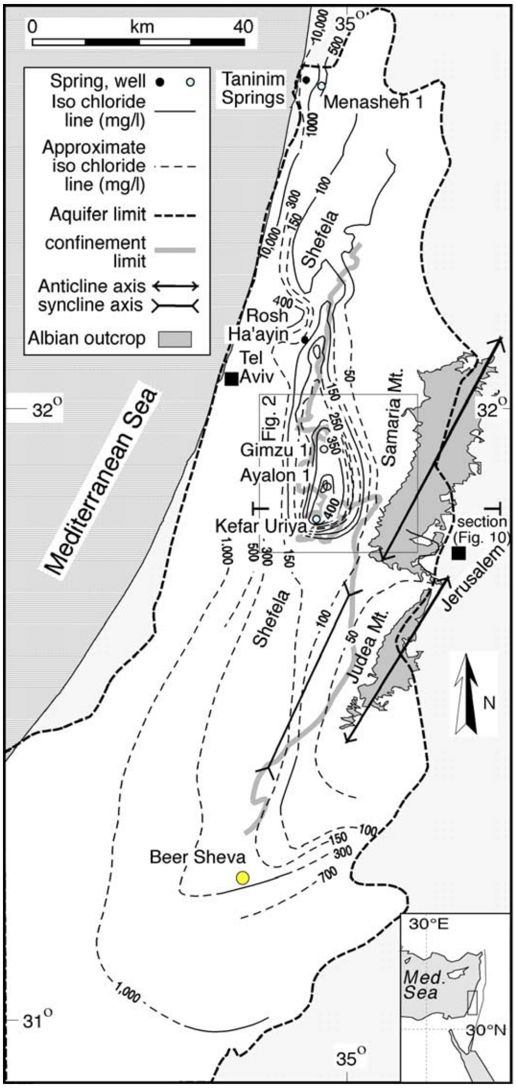

Fig. 1. Salinity map of the upper Yarkon–Taninim aquifer, modified after Mercado (1980) and Weinberger et al. (1994). The Ayalon Saline Anomaly (ASA) is shown by the closed contours around Ayalon–Kefar Uriya. The Albian outcrops in Samaria mountains (gray) are the suggested replenishment zones of the ASA water. The locations of Figs. 2 (the main studied region) and 10 are noted. The eastern aquifers (light shading), beyond the Yarkon–Taninim eastern limit, drain to the Dead Sea base level. The western limit of the aquifer roughly (but not exactly) coincides with the Mediterranean coast.

aquifer. Anomalous brackish groundwater was detected in Ayalon 1 well (Figs. 1 and 2), drilled on 1951, and later also in many adjacent wells (Hydrological Service database). Later, it was found that this anomaly spreads over an area of about 200 km^2, having an ellipsoid form (Fig. 1). Chloride concentration at the center reaches $\sim$500 mg/l, while the 'normal' groundwater all around is 50–100 mg/l. This anomaly is referred to below as the Ayalon Saline Anomaly (ASA).

Because fresh groundwater exists all around the ASA, lateral flow of saline groundwater had been rejected as a potential salination source of the ASA. Eastward flow of saline groundwater from beneath the Mediterranean Sea was rejected based on numerical modeling (Shaharabani, 1976). Most studies attributed the source of the ASA to local infiltration from above (Avisar et al., 2003; Burg et al., 2001; Ecker, 1995; Gavrieli et al., 2002; Greitzer, 1960; Guttman and Etinger, 1996; Guttman and Kronfeld, 1982; Kroitoru et al., 1992; Mandell et al., 2003; Mero, 1978). This 'upper-source' model originated from the observation that salinity decreases with depth in the upper 150 m of the aquifer (e.g. Gimzu 1 and Kefar Uriya 4 wells; Fig. 2). Most of these studies suggested that salts are flushed from the Mt Scopus chalks overlying the aquifer. On the other hand, based on chemical observations of the ASA water, which is different from Mt Scopus leachates, Avisar et al. (2003) and Mandell et al. (2003) postulated that the ASA derives from leachates of soil and rock debris from sub-aerial sources. H_2S presence in the ASA groundwater, indicating anoxic conditions, had been attributed to: (1) decomposition of sewage effluent (Ronen and Kanfi, 1978); (2) leaching of organic-rich rock from the overlying bituminous chalk of Mt Scopus aquitard (Burg et al., 2001; Gavrieli et al., 2002; Guttman and Etinger, 1997). Although the above-mentioned studies are slightly different from each other, all have agreed about the upper-source model. Against these, Frumkin and Arzi (1999) suggested a 'deeper-source' model, and Katz (2001) proposed that the salination occurs by Ca-chloride brines, based on geochemical analyses. In any case, field data are sparse in this area, and thus, a clear hydrogeological understanding is still lacking. Indeed, Weinberger et al. (1994), in their critical review, summarized the previous ASA explanations in the following words: "All these views have been exclusively based upon assumptions without considering lithological, geochemical or structural evidences". In the last decade some information has been

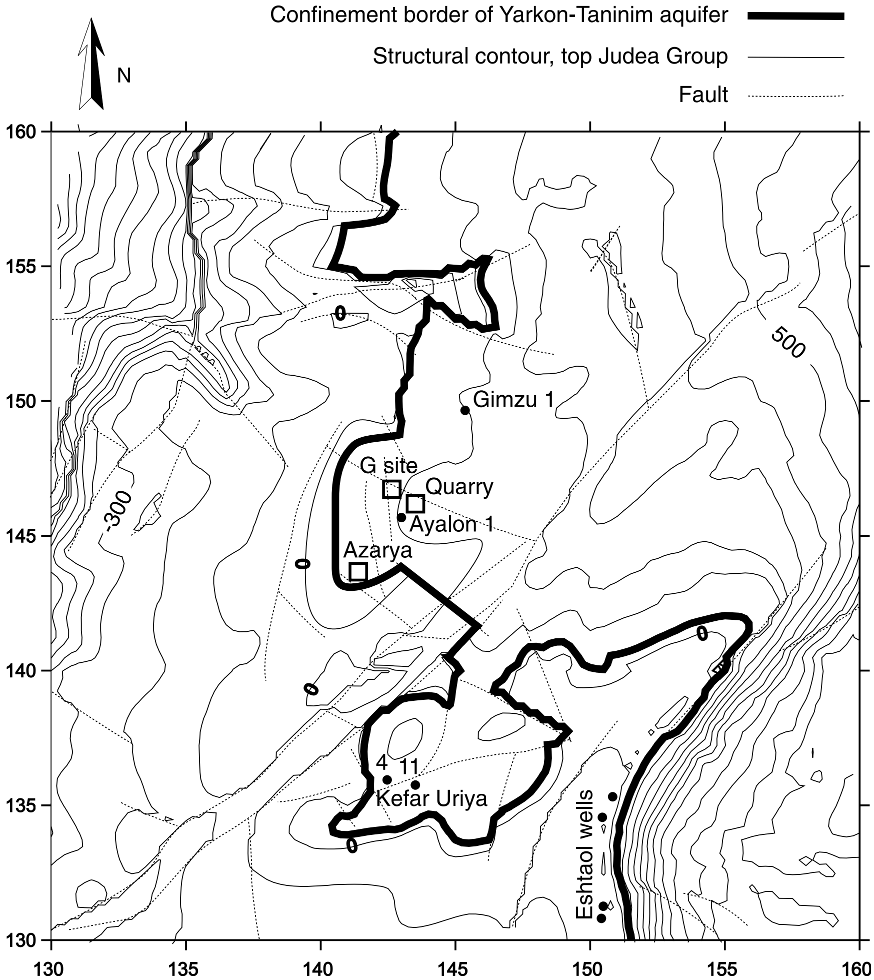

Fig. 2. The main studied region: a structural map of the top of the Judea Group, serving as the confinement surface of the upper Yarkon–Taninim aquifer, with contour intervals of 100 m, modified after Klang and Gvirtzman (1988), Fleischer and Gafsou (2000), and Frumkin (2002). Heavy line shows the border between unconfined (east) and confined (west) zones. The ASA is observed along the westernmost unconfined zone. Full circles are wells; empty squares - study sites with karst features. Israel Grid coordinates (in km).

added by new studies, but a comprehensive approach to the ASA is still lacking.

In this study, we present a new set of data on the ASA, including detailed groundwater monitoring and speleological survey. Thereby, we propose a new conceptual model; namely, a geothermal artesian karstic system with underground springs. Our new model explains the spatial distribution of the anomaly and matches the geological structure. Moreover, it provides insight into ambiguous past hydrologic behavior and suggests some practical management implications.

Geothermal artesian karstic systems have been described elsewhere (Dublyansky, 2000a). Such systems are commonly associated with deep thermo-mineral circulation, and with typical morphological cave features, such as mazes, ceiling cupolas, and lack of genetic relationship to modern landscape (Klimchouk, 2000). Normally, these caves are associated with dissolution under water-filled conditions by slow-moving rising hydrothermal water from a hypogene (deep) source (Bakalowicz et al., 1987; Dublyansky, 2000b). The discharge zone of geothermal artesian karst systems may exhibit cross-formational rising flow associated with large network-like voids (Klimchouk, 2003) and collapse sinkholes (Salvati and Sasowsky, 2002).

Karstic aquifers in general are extremely heterogeneous porous media, because they are characterized by porosity and hydraulic conductivity at both micro- and macro-scales. Groundwater flow through a karstic system is concentrated in a limited number of high-permeability conduits, while the largest part of the water mass exists in the surrounding porous matrix. In some karst settings under unconfined conditions, more than 94% of the flow takes place in karstified conduits, but more than 96% of the storage capacity is included within fissures and matrix pores (Worthington, 2003). Such basins are known worldwide, and many case studies have been recorded in the literature (Ford and Williams, 1989; Klimchouk et al., 2000; White, 1988).

2. Hydrogeologic setting

The Yarkon–Taninim aquifer rocks are predominantly Cretaceous carbonates of the Judea Group, with a total thickness of about 800 m. The Judea Group, of Albian–Turonian Age, is sub-divided in the mountain outcrops into some 10 formations (Fig. 3B). The lower nine, of Albian–Cenomanian age, consist mainly of dolomites interbedded with thin marl layers and some limestone. These are overlain by the Turonian Bina Formation, consisting mainly of limestone. The Bina Formation is overlain by Senonian to Paleocene chalks with some chert and marls, comprising the Mt Scopus Group. In some regions, the Mt Scopus Group is covered by Eocene chalks of the Avedat Group. Late Cenozoic sediments have accumulated mainly along the Mediterranean coastal plain, while recent alluvium is present in most

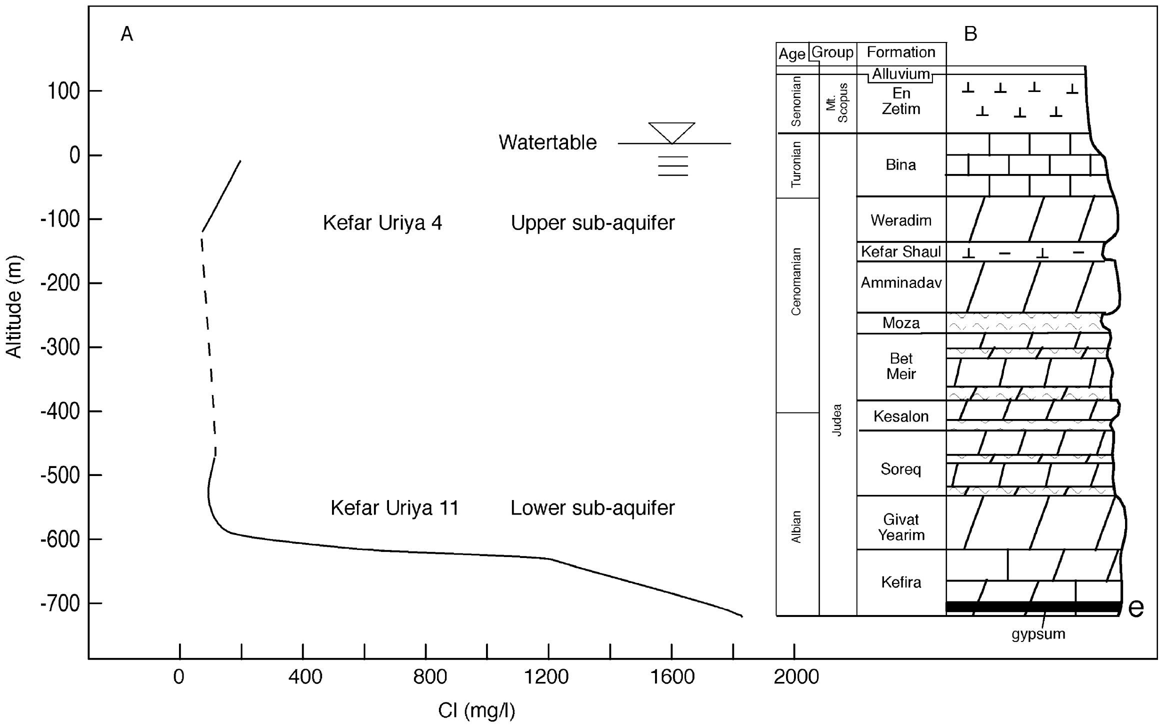

Fig. 3. (A) Salinity profile of western Kefar Uriya region, based on two wells less than 1 km apart: Kefar Uriya 4 (Mero, 1978) and Kefar Uriya 11 (Guttman et al., 2001). (B) generalized columnar section of Kefar Uriya 11 (modified after Guttman et al., 2001; Gvirtzman, 2002). Note the high salinity at the bottom of Kefar Uriya 11, associated with thin evaporite beds. The main lithology is shown schematically in each unit: Albian-Cenomanian rocks are mainly dolomites intercalated by thin marls, Turonian rock is mainly limestone, and Senonian rock is mainly chalk.

valleys. A quarter to a half of the annual Yarkon–Taninim replenishment enters the 'lower sub-aquifer', consisting of Albian to lower-Cenomanian rocks, and the rest recharges directly into the 'upper sub-aquifer', consisting of late-Cenomanian and Turonian rocks (Weinberger et al., 1994). Under natural conditions, before pumping had started, the outlets of the aquifer were only springs, which emerge from the upper sub-aquifer. Human exploitation during the last few decades (300–450 million cubic meters annually) is also derived predominantly from the upper sub-aquifer. The water budget thus implies that most of the natural replenishment to the lower sub-aquifer flows into the upper sub-aquifer. In the southern part of Yarkon–Taninim aquifer, an upward cross-formational flow was indeed demonstrated (Weinberger and Rosenthal, 1994, 1998).

Although the aquifer has been utilized and studied for more than half a century, many of its properties remain unclear, especially at the lower sub-aquifer, which has been hardly drilled. Even the general nature of the Yarkon–Taninim aquifer, whether it is a single continuous basin or several discrete ones is still under debate (Gvirtzman, 2002; Kronfeld, 1997; Weinberger et al., 1994). A common conceptual model (Goldschmidt, 1958; Mandel, 1961) suggests that Yarkon–Taninim aquifer is a single groundwater basin, where the general groundwater flow direction is northwestward. Thus, as one moves along the presumed flow-direction, groundwater should become older, warmer and more saline. However, data contradicting this model have been observed in the central region of the aquifer, thus a different conceptual model has been proposed, suggesting that the aquifer is divided into several discrete basins (e.g. Kronfeld, 1997; Mercado, 1980; Schneider, 1964; Weinberger et al., 1994).

The ambiguous features of the ASA have been observed at the Ayalon and Kefar Uriya well fields (Fig. 1), extending northward along a narrow zone passing through Gimzu 1 well and then between Rosh-Ha'ayin springs and the mountains, terminating a few km north of the springs. The southern extent of the anomaly is not well-known due to the limited number of wells south of Kefar Uriya. The ASA water has been detected only in the upper sub-aquifer. In the southern part of the ASA, Senonian to Eocene chalk and marls crop out, while in its northern part the Senonian to Eocene rocks are often missing or buried.

3. Methods

We have gathered data at the center of the ASA (Fig. 2), where the Turonian limestone crops out and is dissected by a quarry. The quarry (about 1000 m long, 600 m wide, and 100 m deep) cuts down through the limestone, reaching below the historic ground-water level of the early 1950s (+23 m). This has allowed us to closely examine the elusive sub-surface morphology of breached caves. A new dense network of shallow boreholes allowed us to study the groundwater and intersected voids with high resolution (Frumkin and Arzi, 1999), as explained below.

Between November 1998 and September 2002, we sampled 68 new boreholes that descend below the watertable, to study the spatial variability of water characteristics over short distances (few meters to hundreds of meters). Temperature, pH, and electric conductivity were measured on site a few seconds after sampling the water, using portable instruments. Each measurement was made twice and then averaged. Saturation index with respect to calcite and dolomite were calculated using the SI program by A.N. Palmer. Full chemical analyses were performed at the Israel Geological Survey and Nesher laboratories. Uranium and bromide were determined by ICPMS; chloride by ion chromatography; alkalinity by titration within 24 h of sampling; other major cations by ICP-AES; and H_2S by titration after deposition as ZnS. Calculated ion balance errors range from 0.3 to 2.3%.

The morphology of underground voids was studied by standard speleologic surveying methods, using a laser distance instrument (Disto), compass and inclinometer. Morphological elements of the caves have been examined manually and by robot-carried video camera in inaccessible horizontal passages. A submersible video camera was used in boreholes to examine the voids above and below the watertable. The distribution of voids was also studied using detailed records of some 10,000 boreholes, each 25 m deep and 10 cm in diameter. These were drilled in a 7 m resolution grid, as a regular quarrying routine against the danger of potential large voids which may collapse. The location, depth, and vertical size of each void encountered by these boreholes were carefully recorded by the drilling team. Wherever a large void was found (depth size of a few meters), additional boreholes were drilled around, in order to delineate its horizontal limits.

Five new cored boreholes 100-m-deep were drilled at ‘G-site’ where a new power station is being constructed (Fig. 2). Observations at these boreholes included geological analysis, detailed registration of depth and size of voids, and visual examination using borehole video (Frumkin, 2002; Geoprospect, 2002).

Previous groundwater data (from the Hydrological Service database) of the whole region, around and within the ASA, was analyzed and compared to the new data, in order to evaluate the ASA on a regional scale.

4. Results

4.1. Temperature

A groundwater temperature map of the quarry was prepared by on-site temperature measurements at the watertable in 63 boreholes (Fig. 4). Water warmer than 26 °C occurs in three sites in the quarry, referred to below as hot spots (Fig. 4A). On a regional scale, a temperature of 30 °C was measured at G-site (Fig. 2) in the center of the ASA (Frumkin, 2002), compared with an average of 24.7 °C, and a range of 22–26 °C in 95% of the Yarkon–Taninim wells (Ronen and Kanfi, 1978), located mainly in the north-western part of the aquifer (Fig. 1). The ASA water can thus be termed hydrothermal (Dublyansky, 2000b), as it is ~5 °C warmer than the regional groundwater temperature, and 10 °C above mean air temperature (20 °C). Although the temperature anomaly had been observed in the past (Schneider, 1964), its relation to the salinity anomaly had been overlooked, or attributed to local air temperatures (Guttman and Etinger, 1997).

The spatial distribution of elevated water temperature is similar to the occurrence of ASA water (Fig. 5A).

4.2. Groundwater geochemical characteristics

The ASA water is generally brackish, containing significantly higher concentrations of Na, Cl, and SO_4 compared with the ‘normal’ fresh water of the aquifer. This is accompanied by the other ASA hydrothermal features, described above and below.

Within the entire upper Yarkon–Taninim sub-aquifer, a positive Cl-temperature correlation (Fig. 5A) represents a mixing curve between a cool-fresh end-member and a saline-warm end-member. Similarly, H_2S is found only in the warm, brackish water (Fig. 5B). The cool-fresh end-member is the ‘normal’ water type in the upper sub-aquifer.

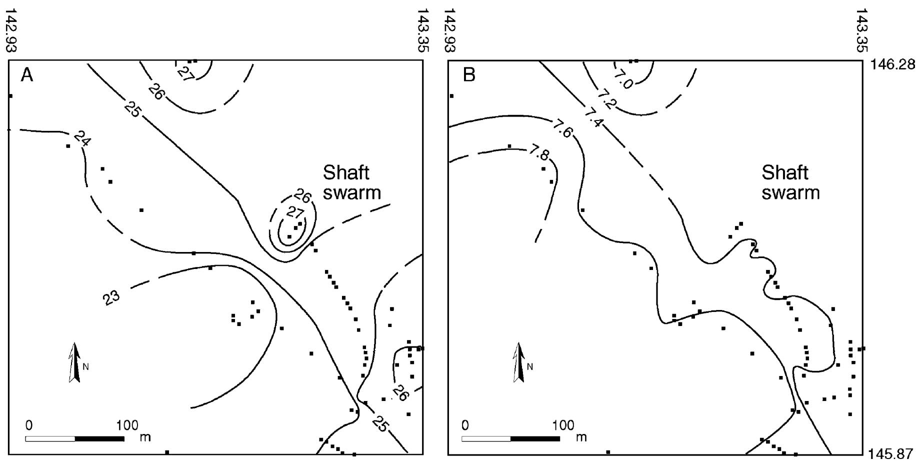

Fig. 4. Groundwater maps of the lower part of the quarry, based on 63 boreholes (black dots): (A) temperature (°C); (B) pH. Note the three ‘hot spots’ with temperatures above 26 °C. Israel Grid coordinates.

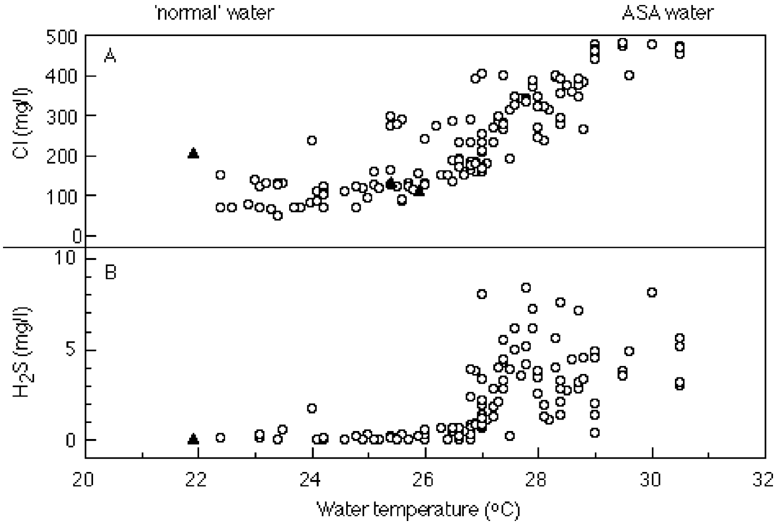

Fig. 5. H_2S and chloride concentration vs. temperature in monitored wells of the entire upper Yarkon–Taninim sub-aquifer (empty circles) and Kefar Uriya 9 well in the Mt Scopus aquitard (full triangles). The chloride–temperature relationship shows distribution along a mixing line of two end-members: a 'normal' cool-fresh end-member common in the aquifer outside the ASA, and a warm, brackish end-member of the Ayalon–Kefar Uriya region (ASA). H_2S appears only in the warm, brackish water. The few samples available of Mt Scopus aquitard water are cool and contain no H_2S, indicating that it cannot be the anomalous end-member of the ASA. Data is from the quarry and 'G-site' (present study, Frumkin and Arzi, 1999; Frumkin, 2002; Geoprospect, 2002) as well as from historic well records (Israel Hydrological Service; Burg et al., 2001).

The 'hot spots' water within the quarry are characterized by lower pH (Fig. 4B) and distinct odor of H_2S. Within a horizontal distance of 100–200 m, the variations of temperature, pH, and Cl concentration approach 5 °C, 1 pH unit, and 400 mg/l, respectively. The lowest values measured in the quarry are within the normal range of the upper sub-aquifer (outside the ASA). Groundwater samples collected in 'G-site' (Fig. 2) boreholes display some of the most anomalous ASA values: temperature, pH, Cl, and total dissolved solids are 29.6 ± 1 °C, 7.0 ± 0.2, 461 ± 13, and 1257 ± 43 mg/l, respectively. Comparing the ASA 'G-site' values with the 'normal' water from the quarry (outside the hot spots), the largest spatial variabilities are observed within a distance of 1 km: temperature, pH, Cl, and H_2S concentrations range spatially between 22.1–30.5 °C, 6.7–7.9 pH units, 42–528, and 0–5.6 mg/l, respectively.

Typical equivalent ratios of Na/Cl, SO_4/Cl, Mg/Ca, Ca/Cl, SO_4/HCO_3 of the ASA water are 0.97, 0.14, 0.85, 0.32, and 0.33, respectively. The respective values of the normal aquifer water are 0.92, 0.23, 0.80, 1.8, and 0.08. This difference mainly reflects the higher concentration of Na, Cl, and SO_4 in the ASA water.

Altogether, the sampled aquifer is extremely non-homogenous. The local spatial variations in the quarry and 'G-site' seem indistinguishable from these of the entire ASA in terms of temperature, pH, salinity, and H_2S. The intense drilling in the quarry demonstrates for the first time this very high spatial variability of the ASA over short distances. Most of the water sampled at the watertable has a saturation index of 0 ± 0.1 with respect to calcite and dolomite, indicating that most aggressive water, if any, has already been buffered by limestone dissolution. Yet, some calculated saturation index values of -0.2 to -0.4 (with respect to calcite) do indicate potentially aggressive water.

4.3. Salinity-depth profile

Wells in the ASA draw water mainly from the upper Judea Group aquifer. Detailed salinity/depth profiles in some of these wells show that the salinity within the upper sub-aquifer decreases with depth (Fig. 3A). This observation led the Israeli water authorities to drill the new Kefar Uriya 11 well (Figs. 2 and 11) to a much greater depth, looking for fresh water within the ASA region. However, within the lower sub-aquifer, at 600 m below sea level, water salinity started rising dramatically, and at 700 m below sea level within Albian beds, it approached 1800 mgCl/l and 3310 $mgSO_4$/l. This brackish water is associated with several beds of Albian evaporites found at the bottom of the borehole (Guttman et al., 2001). The Cl profile (Fig. 3A) suggests that the aquifer may be sub-divided here into three horizontal water bodies: (1) upper anomalous water of the ASA; (2) intermediate fresh, 'normal' water of Yarkon–Taninim aquifer; and (3) deep brackish-water.

The available chemical and isotopic data of the Kefar Uriya 11 brackish water are limited because the lower part of the well was sealed soon after drilling, in order to avoid salination of the overlying fresh water through the borehole. Kefar Uriya 11 is the only borehole drilled into the lower Judea Group aquifer within the central ASA region.

4.4. Karst features

Abundant voids have been observed before within the Bina Formation in boreholes of the ASA region, e.g. Kefar Uriya 4 (Mero, 1978). We have encountered many hundreds of voids of various sizes in the quarry and the 'G-site' (Fig. 2).

The five 'G-site' boreholes (Fig. 2) cut through the Senonian En Zetim Formation (chalk), Turonian Bina Formation (limestone), as well as the upper 15 m of the Late-Cenomaian Weradim Formation (dolomite). Full recovery of the core was obtained in the Senonian chalk, but extremely low recovery in the Late-Cenomaian to Turonian rocks of the upper sub-aquifer (commonly from 0 to 70%). The drill-head fell freely along low-recovery zones, up to 33 m long, associated with numerous karst voids above and below the watertable. The high-porosity rock with variable-sized voids was demonstrated by downhole video too. Comparison of borehole data and field studies show that void porosity in the studied ASA region is at least one order of magnitude larger than in the adjacent non-anomalous region (Frumkin and Arzi, 1999; Frumkin, 2002; Geoprospect, 2002; Frumkin and Fischhendler, 2005). The high porosity in 'G-site' is associated with some of the most anomalous ASA-type geochemical and thermal values known from the upper aquifer. A close association between abundant voids in the upper sub-aquifer and the ASA thermo-chemical features of

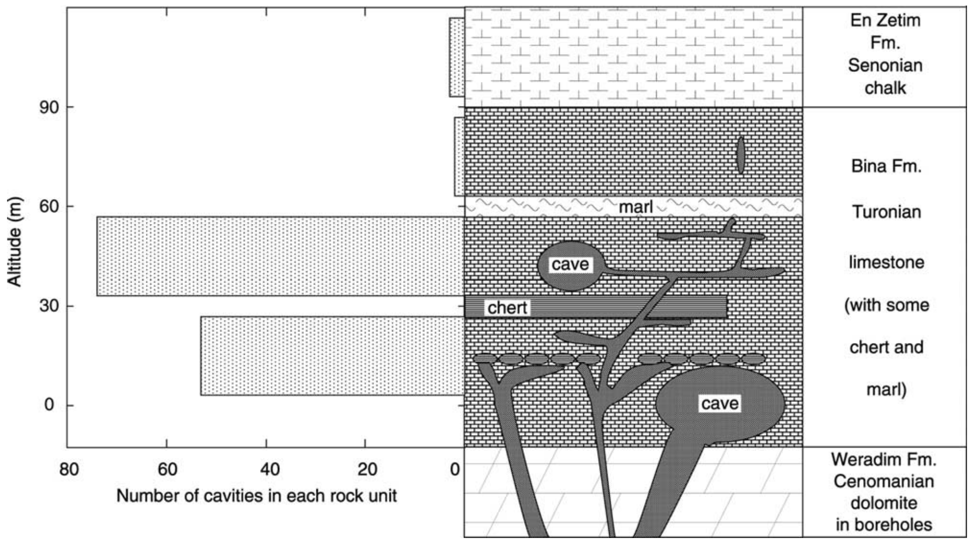

Fig. 6. Generalized section of the quarry, with schematic representation of cave forms and associated altitudes, and histogram (left) of the number of cavities encountered in each stratigraphic unit during this study. The database is from ~10,000 boreholes, each 20 m deep, and direct observation, all within the quarry. The shown histogram represents an arbitrary sample of voids encountered by the quarry from 1997 to 1999, which is the best available approximation of actual void frequency in the ASA. The Weradim Formation is not included in the histogram because it was not breached by the quarry. It was, however, cut by a few boreholes showing frequent voids. Watertable altitude on 1999 was ~+15 m.

the water (above) is also observed in the Kefar Uriya wells (Mero, 1978; Hydrological Service database).

Most of the karstic voids are in the low- to mid-Bina Formation (Fig. 6). In the upper part of Bina Formation (above its thin marly-clastic unit) as well as in the overlying En Zetim Formation there are hardly any natural voids.

We have studied directly over 100 voids, the larger of which are termed caves (Fig. 7). These are supplemented with video observations within inaccessible voids, such as the voids in the Weradim Formation, which is not cut by the quarry but only by boreholes. The caves have no genetic relationship to the land surface. Cave walls and ceilings are mostly smooth, indicating slow-moving water which filled the entire space (Figs. 8 and 9). There is no sign of gravitational (free-surface) or fast flow of water, such as underground rivers. Etching is observed around silicified concretions and fossils, which protrude from the wall. Ceilings are rich in cupola-form solution pockets, having no outlets or inlets which could support groundwater flow into or out of the cave through overlying rocks. Inlet or outlet holes and elongate rift are observed at the bottom of the cave passages (Fig. 9). Warm humid air often emerges today from these holes, dissolving limestome within the rift and depositing calcite rims upon entering the cave passage. The only clastic sediments within the cave passages are fine clays (apart from breakdown debris). Vadose speleothems (such as stalagmites) are rare. No natural entrances of caves are observed.

Three macro-morphological types of underground voids are distinguished according to their three-dimensional form (following Klimchouk, 2000; Frumkin and Fischhendler, 2005):

(1) Vertical (or sub-vertical) joint-guided conduits, or shafts. These shafts reach a diameter of a few meters, but smaller diameters are more common. They extend upwards from below the watertable, commonly up to a thin impermeable layer of chert or marl, within the Turonian limestone (Figs. 6 and 8). The shafts terminate there abruptly and/or divert into lateral conduits, which extend horizontally from the top of the shafts. The shafts are spatially concentrated in ‘swarms’ of up to 10 individual shafts. The most prominent swarm is observed at the center of the quarry (Fig. 4).

Fig. 7. Plans of typical horizontal caves in Turonian limestone in the Ayalon 1 region. Maze (network) pattern of conduits commonly develop along one or several bedding planes. Cave entrances are artificial. (A) ‘Cave 4’, coordinates 14349 14597; (B) Aneva Cave, 14347 14591, broken lines are elongated rifts at the bottom of passages (Fig. 9); (C) Zickron–Aneva Cave, 14310 14635.

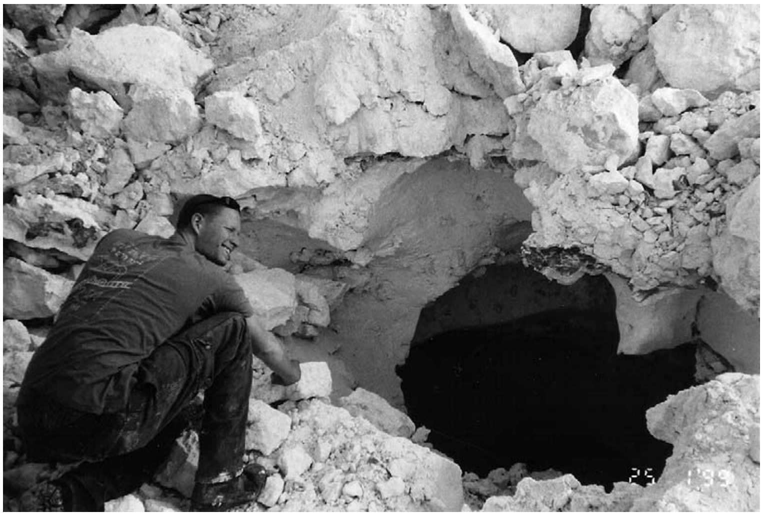

Fig. 8. A typical vertical shaft in the lower Bina Formation in the center of the quarry. The shaft terminates upwards at a black chert layer (middle right), which was intersected by quarrying. Note dissolution pockets and smooth walls of the shaft. The bottom of the shaft is close to the present watertable.

Shafts have been explored down to a depth of < 10 m, where they are usually blocked by quarrying debris.

(2) Horizontal (or sub-horizontal) conduits, formed along bedding planes/joints intersection. These conduits are often interconnected, forming three-dimensional network (maze) up to hundreds of meters in length (Fig. 7). The water source of these systems is at the bottom of the conduits, either as individual phreatic shafts or elongated fissures along the axis of the conduit (Fig. 8). The horizontal conduits terminate some tens of meters away from the source shaft.

(3) Large-diameter (up to ∼40 m) voids and sinkholes. Sites with intensive karst-induced subsidence are reflected by bedrock inclinations towards the center of dissolution, forming ‘tectonokarstic synclines’ of 10–200 m in diameter in relatively unconsolidated rocks. It is hard to detect the original dissolution morphology of the initial voids, which is often obscured by debris. Collapse sinkholes are relatively rare, but they endanger life and property. Catastrophic collapse events occurred naturally in 1979 and 2001 in Azarya village (Fig. 2), forming sinkholes tens of meters deep, a few meters away from inhabited houses.

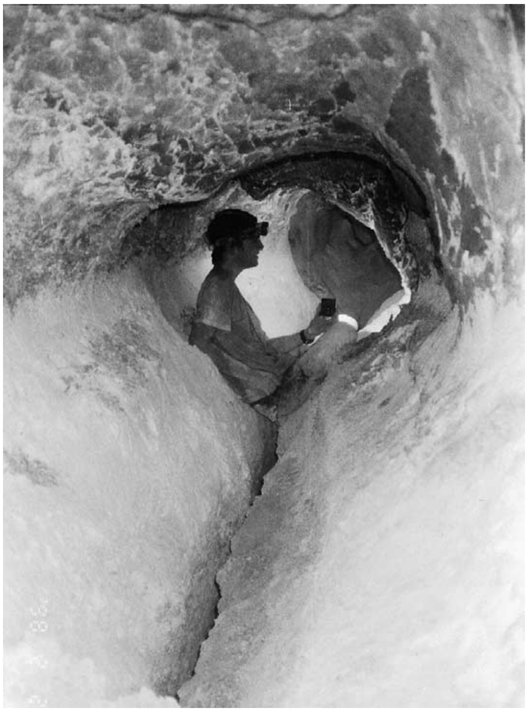

Fig. 9. A typical horizontal passage in the network of Aneva Cave (Fig. 7B). Note the smooth walls, lack of any open fissures at the ceiling, planes of repose of insoluble residues at the lower surfaces, and, most significantly, elongate rift at the bottom of the passage, which served as water feeder.

Various types of voids are often associated with each other, and intermediate forms are common. Longer maze-type horizontal caves (Fig. 7) are found at the top of the karstified zone, within the mid-Bina Formation. In deeper levels, within the lower Bina Formation, vertical shafts and large chambers are more abundant. Boreholes demonstrate that cavities extend well below the present watertable.

4.5. Hydraulic properties

The relative discharge of wells in the ASA region is 5000–10,000 m^3/h, much higher than the 300–2000 m^3/h observed in most other pumping wells of the aquifer (Hydrological Service database). For example, no measurable drawdown was observed in the wells Ayalon 5, Kefar Uriya 4, Kefar Uriya 5, and Kefar Uriya 6, during pumping tests. Considering the observed high karstification, this phenomenon is expected.

The watertable at the Ayalon 1 well (Figs. 2 and 10) has recently fluctuated between the mid-20th century high level of over 23 m, which was regained on 1993 following high precipitation, and levels ~11 m lower on 1991 and 2001, following several years of low precipitation and intensive pumping from the aquifer (Fig. 10A). No pumping or dewatering has been conducted in the quarry; groundwater level in the quarry follows closely the level in the adjacent area recorded in Ayalon 1 well.

Following rainy events, the groundwater level in the ASA region (observed in Ayalon 1 well) rises faster and to a higher level than in the other parts of the aquifer in the Shefela (Fig. 1). The largest recent recharge occurred in 1991–1993 (Shachnai and Tsukerman, 1999) when precipitation amount was almost twice the mean annual precipitation. By spring 1993, the water level at Ayalon 1 rose by 11.5 m (compared to autumn, 1991), reaching a maximum level of 23.5 m above sea level (Fig. 10A). The coeval rises at the southern Beer Sheva observation well and northern Menasheh 1 well (Fig. 1) were only ~5 m. A temporary water mound centered at the ASA was thus formed (Fig. 10B), with levels higher in the ASA than in the southern and northern parts of the aquifer (Ecker, 1995; Shachnai and Tsukerman, 1999). Following spring 1993, there was a much drier decade. Water levels in Ayalon 1 dropped down to the level in Beer Sheva observation well and lower. This caused a reversal of the flow direction: southward flow from the ASA region in 1992–1994, and then northward flow from Beer Sheva in the late1990s.

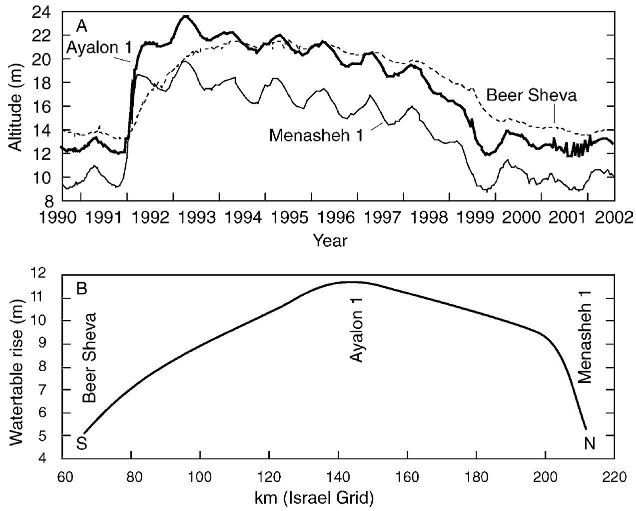

Fig. 10. Yarkon–Taninim aquifer water levels (data from the Israel Hydrological Service): (A) A 12-year-long level record of three observation wells from the north (Menasheh 1), center (Ayalon 1) and south (Beer Sheva) parts of the aquifer. (B) Relative change of water level from November 1991 to April 1993 along a north–south transect.

Eastward flow (a very uncommon flow direction of the aquifer) has been observed within the upper sub-aquifer from Kefar Uriya towards Eshtaol (Fig. 2; Mero, 1978). This flow direction can be explained by the water mound at the ASA, although part of it may result from the intensive pumping in Eshtaol wells. The relation between the ASA and Eshtaol waters is further revealed by the concentration of radiocarbon and tritium measured during 1984–1986 by Kroitoru et al. (1992). The ASA water at Kefar Uriya 4 well was richer in these isotopes compared to those the Eshtaol wells, (Fig. 2), indicating that the ASA water is recharged faster than Eshtaol, although Eshtaol is closer to the mountain recharge zone of the aquifer.

5. Discussion

The 'hot spots' (∼30 °C) and the associated ASA chemistry cannot be explained by the commonly postulated 'upper-source' model. Neither local mean air temperature (20 °C on the average) nor any exothermic reaction in the Mt Scopus Group rocks can cause such a stable thermal anomaly. Indeed, groundwater at Kefar Uriya 9 well, pumped from the Mt Scopus aquitard, is too cool (22–26 °C) to represent the anomalous temperature (Fig. 5). Moreover, the Mt Scopus chalk is missing at the hot spots mapped in Fig. 4.

In addition, the spatial distributions of Mt Scopus rocks and/or the cover soil do not fit the spatial distribution of the anomalous salinity. For example, in most of the northern ASA region no Mt Scopus rocks exist above the Judea Group, mainly because of erosion which followed tectonic uplift. Similarly, the soil coverage is not limited to the ASA region and it covers only a part of this region.

The possibility that the anoxic conditions are derived from decomposition of sewage (Ronen and Kanfi, 1978) is ruled out, because elevated H_2S was recorded at Ayalon 1 already on 1951, prior to any large-scale sewage contamination. Seepage of saline organic-rich water from the bituminous chalk of Mt Scopus aquitard is also ruled out because neither such water nor H_2S-rich water have been recorded in the Mt Scopus aquitard (given that several water samples were analyzed; Mero, 1978; Ecker, 1995; Burg et al., 2001). Even if such water does exist somewhere, its discharge must be small due to the low permeability of the Mt Scopus Group compared with the excellent hydraulic properties of the underlying Judea Group aquifer at the ASA.

We suggest that the observed 'hot spots' and their associated chemistry can be explained by upward flow from a deep hydrothermal and saline groundwater source. This hydrothermal water mixes with the freshwater of the upper sub-aquifer, producing a spectrum of water types ranging between the two end-members. The presence of H_2S, a common feature of thermomineral circulation (Dublyansky, 2000a), also indicates a deep, anoxic source of the hydrothermal groundwater. Cross-formational rising flow is common in artesian karst basins (Klimchouk, 2003).

The deep brackish water sampled in Kefar Uriya 11 well, ∼700 m below sea level, may represent the deep end-member of the ASA, before this water flows upwards to the upper sub-aquifer. This assumption is supported by the limited data available from this borehole. Chlorides and $\delta^{34}S$ of dissolved sulfates at the bottom of Kefar Uriya 11 well are 1480 mg/l and 13.3‰, respectively (Guttman et al., 2001). The respective values for the eastern Kefar Uriya wells, which are hardly affected by the ASA, are 100–200 mg/l and 1–2.4‰ (Gavrieli et al., 2002). Other values for the upper sub-aquifer in the ASA fall close to a straight line between these two waters, indicating mixing of these two end-members. ^{34}S enrichment occurs due to fractionation associated with bacterial sulfate reduction, which is common under deep anoxic conditions. This may therefore explain the occurrence of H_2S in the ASA.

Dissolution of Albian evaporites associated with the deep Kefar Uriya 11 brackish water (Guttman et al., 2001) seems to be a good candidate for the salinity source of the hydrothermal saline end-member of ASA. Alternatively, a relict of deep brine may contribute to the observed salinity (Katz, 2001; Starinsky, 1974). The equivalent Na/Cl ratio in the ASA water is 1 ± 0.05 (Katz, 2001), which is in agreement with dissolution of evaporites rather than with evaporated seawater. Further study is needed to identify the original source of salinity.

The decreasing salinity with depth in the upper sub-aquifer suggests that the anomalous flow is concentrated in a limited number of high-permeability conduits, which do not affect the 'normal' fresh-water around the conduits. Such a phenomenon commonly occurs in maturely karstified rocks (Worthington, 2003). The existence of deep sub-vertical conduits, as observed at shallow depth, would allow the deep water to reach the shallow ASA zone with hardly any effect on the surrounding low-permeability water under the upper sub-aquifer. Wells have a negligible chance of hitting a *deep* sub-vertical conduit because of its small aerial extent. Cross-formational upward flow may be impeded in the mid-Judea Group by its abundant thin marl layers (Fig. 3), which would occlude developing conduits by accumulation of insoluble residues. However, upward flow promotes the suspension of fine clastic sediment, as opposed to downward flow. Residual clay sediments tend to settle again along horizontal cave passages, where they often mantle sloped repose surfaces (Fig. 9). Among the conditions that would promote cross-formational upward flow: (1) upward hydraulic gradient; (2) tectonic disturbance (major faults and fractures) allowing incipient water flow and initiation of conduits; (3) aggressive water; and (4) turbulent flow which can remove released insoluble clastics.

The high distribution of voids in the upper sub-aquifer in the sites where the ASA was drilled or exposed indicates that these voids are closely associated with the special ASA geochemical, thermal and hydraulic features. Significantly, the high porosity and permeability of the caves must contribute to the excellent hydraulic properties of the upper sub-aquifer in the ASA region. These properties must affect also the ‘normal’ water end-member of the ASA. The high distribution of voids in the ASA is thus reflected by the following features: the mound of water created following high precipitation events; the flow from ASA to all directions; the high relative discharge of wells; the high tritium and radiocarbon values.

The observed morphological features of the caves are known worldwide, and are commonly associated with dissolution under water-filled conditions by slow-moving rising hydrothermal water from a deep (hypogene) source (Dublyansky, 2000b). The plan of the caves, however, is determined by local structure: bedding planes and fractures determine the maze structure of some ASA caves (Fig. 7), comparable to the Black Hills, South Dakota (Bakalowicz et al., 1987).

The observed swarms of vertical shafts represent the conduits through which the aggressive water was injected upwards. The discrete plumes of water rise through the shaft feeders to the upper sub-aquifer, and subsequently disperse laterally close to the watertable through interconnected voids, creating the ASA.

Today, the voids at the quarry extend up to ~50 m above the watertable, indicating either regional uplift or watertable fall since the development of the high-level caves. The vertical distribution of caves above and below the watertable indicates continuous dissolution and cave-formation over time, under a changing watertable regime. On a geological time scale, regional watertable elevation depends mostly on Mediterranean Sea level, so the depth of karstification must have been low during low sea level events (such as the Quaternary glacial periods) and high when sea level was high. These fluctuations modulate the long-term watertable lowering (relative to lithological units) due to tectonic uplift. The spatial location of the ASA apparently remained relatively stable during these vertical modifications, due to the relatively flat topography and the vertical orientation of the voids carrying most of the water.

The relation between geologic structure and the vertical hydraulic gradient controls the spatial location of the ASA. Albian rocks, cropping out at the recharge zone along the crest of the mountain anticlines (Fig. 1) become confined on the western flanks, under the mid-Judea Group marls (Figs. 3B and 11). These conditions are ideal for deep circulation within the Albian beds towards the Shefela. The hydraulic head within the Albian beds must be higher than the head within the overlying Cenomanian-Turonian beds whose confinement occurs at elevations lower than the Albian outcrops (Fig. 11). Such a differential head gradient was indeed measured in deep wells, such as Gimzu 1 (Shachnai, 1980). Relatively fresh water arriving laterally through the overlying Cenomanian beds (~200–600 m below sea level) is observed in wells (Fig. 3), but its lower head does not allow it to rise towards the watertable at the ASA region.

The specific location of rising hydrothermal flow creating ASA is determined by the following conditions: Westward of the ASA zone the Judea Group is deeply buried and confined by thick impervious beds. Along this confinement border

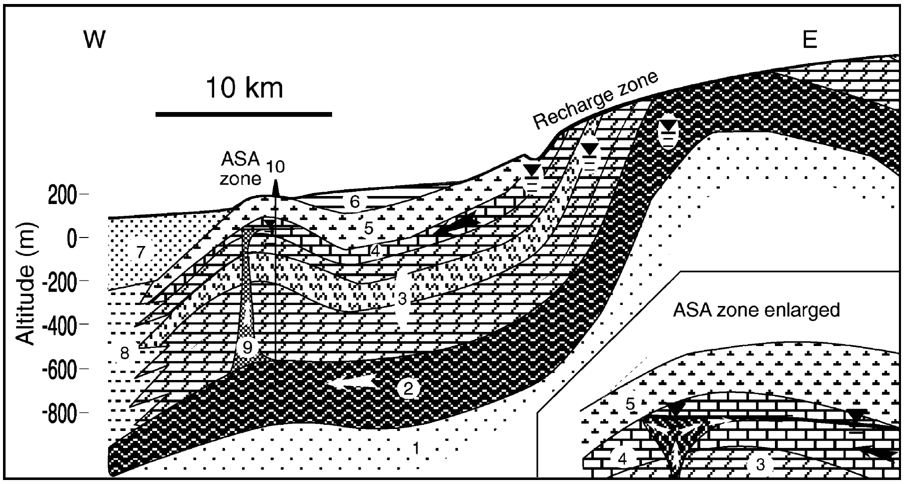

Fig. 11. Schematic east-west hydrogeological cross-section showing the proposed conceptual flow model for the Yarkon–Taninim aquifer from the recharge zone to the ASA zone at Kefar Uriya. (1) Pre-Albian rocks; (2) Albian carbonates and marl; (3) Cenomanian dolomite and marl; (4) Turonian limestone; (5) Senonian chalk; (6) Eocene chalk; (7) Oligocene-Quaternary sediments; (8) Cretaceous chalk and marl; (9) Fractured zone with suggested upward flow; (10) Location of Kefar Uriya 11 well. White arrows - hydrothermal water; black arrow - 'normal' fresh water. Insert shows the inferred plume of hydrothermal water rising and then flowing laterally.

there is a maximum hydraulic gradient between the deep (high-head) sub-aquifer and the watertable, becoming the focus of upward flow. The ASA occurs especially where the unconfined zone extends in the form of tongues to the west or southwest due to local uplifted blocks (Fig. 2). This is evident in Kefar Uriya region, where a local anticline with associated unconfined conditions is almost totally surrounded by structurally lower regions, in which the upper sub-aquifer is confined (Figs. 2 and 11). The situation is similar to the north, at the Azarya/Ayalon/quarry/'G-site' area.

The location of the ASA at the unconfined zone, close to the confinement border is further explained by the fact that unconfined storage capacity is at least several times larger than confined storage capacity (Freeze and Cherry, 1979; Fetter, 1994). At the Yarkon–Taninim aquifer, phreatic and confined storativities are equal to $3–8\times10^{-2}$ and $10^{-4}–10^{-5}$, respectively (Dagan and Kahana, 1997; Gvirtzman, 2002). The upward flow occurs where the upper sub-aquifer is still unconfined, so the water has much larger free space to fill, compared with the nearby confined zone. Approaching the watertable, the emerging rising flow can easily travel laterally along the highly permeable karstified zone. The rising ASA water is comparable to artesian springs, which discharge in the zone of lowest head. The difference is that in the case of the ASA, the upward flow does not reach the land surface, but disperses laterally at the watertable. It may thus be considered an 'underground spring'.

Northward of Ayalon region, the ASA extends as a narrow belt along the westernmost unconfined zone, but its magnitude gradually diminishes. Salinity and temperature anomalies are still observed a few km northwest of Rosh Ha'ayin springs (Fig. 1; Mercado, 1980; Schneider, 1964), but are small. The H_2S anomaly seems to extend northward only as far as ~3 km south of the springs (Guttman and Etinger, 1997). The extension of the ASA north of Ayalon region probably indicates to additional vertical upward flow north of Ayalon region. Alternatively, some lateral northward flow of anomalous water from the Ayalon region along the flow route of the upper aquifer cannot be ruled out.

The ASA water has been in prolonged contact with carbonates of Judea Group, and has thus become chemically saturated with respect to dolomite and calcite. However, the enhanced karstification close to the watertable indicates a rejuvenated dissolutional capacity for the rising water. The following processes may account for the increase of aggressivity of the water: (1) cooling of hydrothermal waters; (2) addition of salt to 'normal' bicarbonate water, inducing undersaturation by the 'ionic strength effect'; (3) sulfate reduction producing H_2S; and (4) mixing of two kinds of saturated waters.

The evidence presented above shows that most probably the following processes indeed add renewed aggressivity to ASA water: (1) the considerable cooling of the rising hydrothermal waters as they equilibrate with cooler rock and cool 'normal' water close to the watertable; and (2) the widespread occurrence of H_2S in the ASA water, acting as a weak acid. Additional aggressivity may be introduced by the mixing of the two types of waters, even if they are previously saturated. The evaporites encountered in Kefar Uriyah 11 borehole probably add salt to the deep circulation of 'normal' bicarbonate water, inducing undersaturation by the 'ionic strength effect'. An upward flow of water through the thick Albian-Cenomanian dolomite beds may become saturated with respect to dolomite, but as it reaches the more soluble Turonian limestone, it may still be undersaturated with respect to calcite. No evidence has yet been encountered for dissolution by H_2SO_4, derived from oxidation of H_2S. This is potentially a very aggressive agent, and it cannot be ruled out (Palmer, 1995). Further study is still needed to estimate the significance of each process.

It remains to be discussed why a deep flow route (indicated by the uptake of salinity and heat $\sim$700 m below sea level) is favored over shallow flow routes connecting the replenishment area to the ASA. The main prerequisites for such a deep flow are confinement of the Albian beds, and enhanced lateral hydraulic conductivity in them. Several effects may enhance the lateral flow from the replenishment area to ~ -700 m under the ASA: (1) Mediterranean regressions, especially during the Messinian crisis, which resulted in entrenchment of canyons and deepening of regional groundwater circulation (Gvirtzman, 1969). This could initiate deep conduits which could continue to function during the following ingression and associated rising watertable. (2) Deep-seated enhancement of dissolution capacity by processes such as addition of salt to 'normal' bicarbonate water; sulfate reduction producing H_2S, or increasing acidity by deep CO_2 sources. (3) Deep dissolution of Albian evaporites may have enhanced the initial permeability of a predominantly carbonate rock sequence. Although gypsum dissolution is commonly associated with calcite deposition (through the common ion effect), the calcite occupies a smaller volume, enhancing overall porosity. This may promote the inception of conduits at great depth, where waters are equilibrated with respect to carbonate minerals (Lowe, 2000; Worthington, 1991). Over geologic time, uplift and erosion of the mountainous recharge zone favors the exposure of deeper beds, which may produce tiers of conduits at successively deeper stratigraphic positions.

The elevated tritium and radiocarbon values in the ASA water indicate that it is younger than in Eshtaol well water, but includes a significant component whose age is several years or decades. An age of several years or decades is in agreement with the elevated-temperature of the water, indicating a good water-rock contact at the deeper flow segment. Intense precipitation, such as occurred in 1992-3, may flush much of the aquifer voids, and inject younger water into the ASA region.

High porosity and high relative discharge of wells, associated with interconnected voids, is a common feature also in other karstic artesian basins (Klimchouk, 2003). This increases the probability of boreholes intersecting the anomalous water, as indeed observed close to the ASA watertable.

6. Conclusions

Most existing models and consequent management policy assume that the Judea Group aquifer and associated aquitards are horizontally homogenous. This assumption is incompatible with our new data, indicating that the Yarkon–Taninim aquifer hosts vertical conduits, which locally increase permeability by many orders of magnitude. The ASA is the discharge area of an artesian karst system, characterized by an intensive vertical hydraulic connection between distant aquifer formations (Fig. 11). As is common in karst groundwater systems, the Yarkon–Taninim aquifer is heterogeneous and non-isotropic at both macro- and micro-scales. Therefore, the flow field in the Yarkon–Taninim aquifer is very complex, characterized by the 'conventional' westward and northward flow directions along with upward and even eastward and southward flow directions at some specific locations and periods.

We argue that the ASA phenomenon exhibits a cross-formational rising thermo-mineral groundwater which is typical to artesian karstic systems. Instead of the previously accepted 'upper-source model' for ASA, we support the 'lower source model', which best explains the ASA observations (Fig. 11). Our conceptual model consists of four-segment flow route (Fig. 1): (1) rainwater recharge through the Albian outcrops; (2) lateral confined flow down to a depth of ~ -700 m; (3) pressurized upward flow through discrete vertical conduits; and (4) multidirectional pervasive flow close to the watertable, forming a kind of 'underground spring' with restricted output, in which the rising water mingles with the 'normal' upper aquifer water. Maze caves fed by vertical conduits are typical for such an 'underground spring', as they disperse the flow laterally in many similar routes. Intensive cave-formation is observed to be associated with the upward flow of aggressive water. Within the 'underground spring' the aggressiveness is consumed over short lateral distances from the vertical feeder (Palmer, 1991). The formation of large voids by dissolution far from the recharge zone implies renewed hydrochemical aggressivity. Further research is needed to determine the exact mechanism renewing the aggressivity.

The spatial location of the ASA is determined by three conditions allowing upward leakage from the deep sub-aquifer: (1) the localization of westernmost unconfined zone of the upper sub-aquifer, and its association with nearby confined regions; (2) large upward head gradient; and (3) spatial heterogeneities of the vertical permeability, associated with tectonically disturbed zones.

Considering water management implications, lowering of the upper aquifer level by pumping may increase the upward gradient and enhance the upper aquifer salination, especially at the ASA borders. The safety hazard of large voids associated with the ASA should be considered in building and quarrying in the ASA region.

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