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Stagnant aquifer concept Part 2. Small scale artesian systems — Hazeva, Dead Sea Rift Valley, Israel

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Abstract

The literature of groundwater hydrology deals almost exclusively with through-flow aquifers, i.e. bodies of permeable rocks that contain water in all their voids, and have active recharge, appreciable through-flow and adequate discharge. The present paper augments this picture by addressing groundwater systems with the likely occurrence of stagnant aquifers, i.e. bodies of permeable rocks that contain water in all their voids, but are sealed off from recharge and discharge, and thus have no water through-flow. A phenomenological approach, based on first principles of physics, geology, hydrology and chemistry, is applied in the present account because groundwater is a concealed fluid that can not be traced directly.

Hydraulically isolated pressurized (artesian) aquifers are identified in continental rocks of the Hazeva Formation, Miocene, in the Hazeva area, within the Rift Valley. The different aquifers are defined by the properties of waters ascending in artesian wells, e.g. concentration of major ions, ^{14}C-based water ages, isotopic composition, and hydraulic heads.

The different pressurized aquifers are interpreted as hydraulically isolated stagnant aquifers because: (1) the continental host rocks reveal a high degree of facies changes, and permeable rocks occur in lenses of limited extension, alternating with impermeable rocks, (2) the present climate is extremely arid and no effective recharge is observed, (3) the groundwaters analyzed in the region contain no measurable tritium, and ^{14}C ages range from 1000 to more than 25 000 years, and (4) the hydrogen and oxygen isotopes indicate recharge occurred under different paleo-climates.

According to the conceptual model suggested, the currently stagnant aquifers are fossil through-flow aquifers that have each been cut off from recharge by overlying impermeable sediments and their discharge stopped by burial beneath the active base of drainage. The artesian pressure is attributed to compaction by overlying rocks.

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The Hazeva trapped pressurized groundwater systems are of special interest as they are (1) young, i.e. 1000 to more than 25 000 years old, (2) shallow, i.e. 50–250 m deep, and (3) small — the aerial extension of individual groundwater traps being in the range of 10 to 10^2 km^2.

The identification of stagnant pressurized groundwater systems warrants special attention because establishment of their existence opens new economic applications, possibly surpassing the importance of the traditional exploitation of self-flowing groundwater. The potential value stems from the basic properties of entrapment: (1) the isolation from any recharge and contact with the surface makes such systems immune to contamination, thus providing ideal water reservoirs for emergencies caused by pollution accidents, including nuclear disasters, and (2) the lack of discharge makes depressurized (exploited) stagnant groundwater systems potential repository sites for toxic and nuclear wastes, freed from the danger of uncontrollable hydrofracturing.

1. Introduction — through-flow and stagnant artesian aquifers

Traditionally, hydrologists consider that an artesian aquifer consists of an outcrop section that acts as a phreatic aquifer through which recharge occurs, and a longer confined section through which groundwater flows to a discharge location. The artesian pressure is, accordingly, attributed to the high hydraulic head in the phreatic section (Fig. 1). The essentials of this model are: (1) a recharge area and a discharge area do exist, (2) the artesian pressure originates by the hydraulic head in a phreatic section, (3) through-flow is maintained. The term 'pressurized through-flow aquifer' is suggested for such an artesian aquifer that has recharge and discharge connected by through-flow.

A competing model (Fridman et al., 1993), tailored for case studies of the type described here, envisages the artesian wells as tapping groundwater that is trapped in rather horizontal permeable rock lenses (Fig. 2), covered by overlying younger sediments constituting aquicludes and aquifers, so they are: (1) sealed from the surface, having no recharge area, (2) buried beneath the base of active drainage, and sealed, so no discharge exists, (3) with no through-flow, (4) of limited local extension, and (5) pressurized by compaction, induced by overlying rocks. The

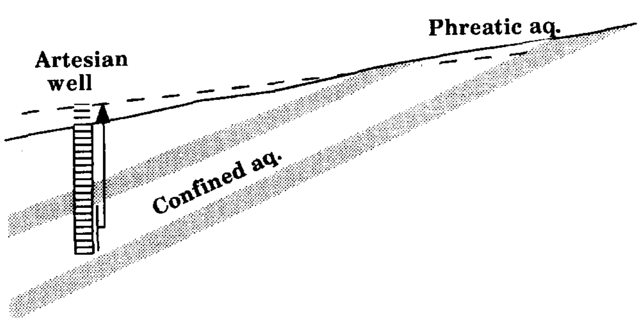


Fig. 1. The classical concept of a through-flow artesian aquifer.

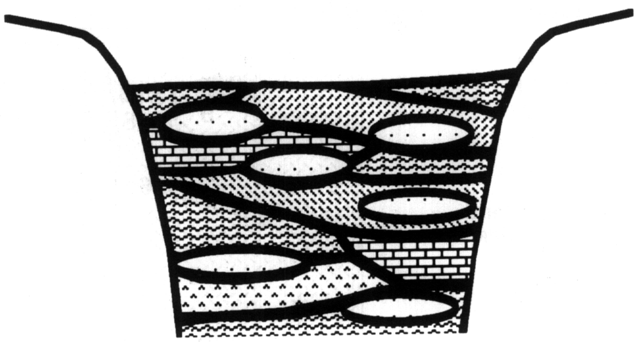


Fig. 2. A suggested model of stagnant artesian aquifers in the variegated sediments of the Rift Valley, constituting pressurized groundwater traps.

term 'stagnant pressurized aquifer' is suggested for such a trapped artesian aquifer that hosts stagnant groundwater.

A crucial aspect of hydrology is the concealed nature of groundwater. Groundwater can be traced with artificial markers only in certain setups, over small distances, and for short time intervals. Larger systems, and especially confined aquifers, can be studied only indirectly — by a phenomenological approach. In this frame the study of real cases is based on detailed measurements, leading to hydrological models that are then evaluated in the light of first principles of physics, hydrology, lithology, structural geology and chemistry. To define the nature of an artesian aquifer as through-flow or stagnant, the hydrological and geological data have to be augmented by direct measurements of the groundwater properties, e.g. hydraulic head, chemical and isotopic composition, temperature, and concentration of age indicators.

Stagnant artesian aquifers may sound plausible in the context of old geological formations that are deeply buried in large inland subsidence basins. But do they occur also in relatively young and small systems? This question is addressed in the present paper, in the light of data from artesian wells drilled into the Hazeva Formation (Miocene) rocks, situated in the northern section of the Arava segment of the Dead Sea Rift Valley, Israel (Fig. 3).

The Arava Rift Valley is bounded by mountains to the east and west, and the surface drainage of the northern section flows into the Dead Sea Basin. Traditionally, hydrologists assumed that all the groundwater in the northern section of the Arava Valley is flowing into the Dead Sea Basin as well. In this context it was suggested that the artesian systems encountered in the northern Arava Valley are through-flow systems that drain into the Dead Sea and are recharged somewhere through outcrops in the mountainous margins of the Negev and/or Sinai (Shiftan, 1961; Gat and Galai, 1982; Arad et al., 1984; Issar, 1985; Yechieli, 1987; Yechieli et al., 1992).

The special interest in the artesian wells of the Hazeva area (Fig. 3) lies in: (1) the detailed information available from wells that are 10^2–10^3 m apart, (2) the shallow depth at which artesian water is encountered, 50–250 m, (3) the location in the young Hazeva Formation (Miocene), (4) the diversity of water properties observed in

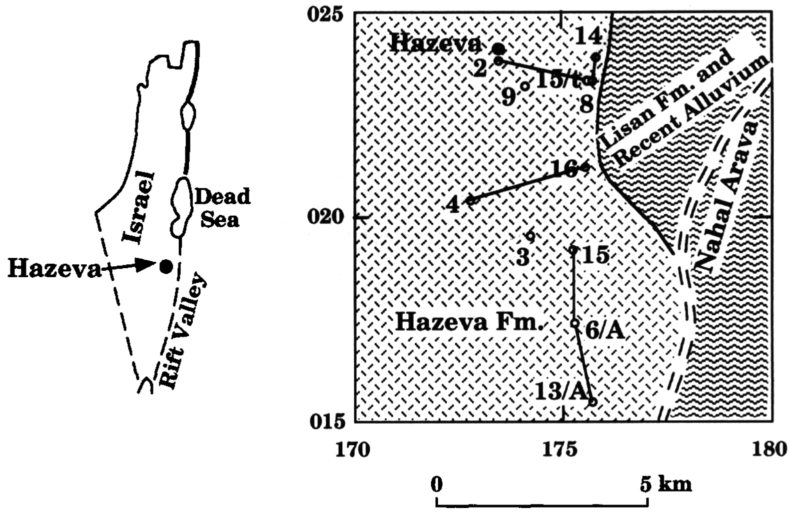


Fig. 3. Location of wells studied in the Hazeva area, and major formations (taken from the Geological Map of Israel 1:250 000). Lines depict transects given in the following figures.

adjacent wells, (5) the lack of observable recharge areas, and (6) the young water ages, in the range of 1000 years up to the limit of the ^{14}C-dating method, i.e. more than 25 000 years.

The present account neither presents a comprehensive study of the groundwater system of the Hazeva region, nor discusses the through-flow suggested for the confined continental rocks of the Nubian Sandstone sequence in the Negev and Sinai (this will be addressed elsewhere). The present communication focuses merely on the plausible existence of a number of distinct aquifers that are hydraulically isolated, i.e. stagnant, and that do not discharge to the Dead Sea Basin. The research strategy included the following stages:

(1) establishment of an atmospheric origin of the dissolved chloride in the artesian waters encountered;

(2) application of the concentration of atmospheric Cl and other ions, hydraulic heads, tritium and ^{14}C ages of water tapped in adjacent wells to identify distinct aquifers, and to establish their spatial extensions;

(3) application of ^{18}O and ^{14}C data to establish that recharge of the different aquifers occurred under different paleo-climate regimes;

(4) application of physical considerations to weigh the through-flow model versus the stagnant model in the studied artesian aquifers;

(5) deduction of management conclusions.

2. Atmospheric origin of the chloride dissolved in the groundwaters studied

Two possible major sources of Cl dissolved in groundwater are: (1) an atmospheric origin, i.e. sea-derived airborne salt (including such salts stored in the soil zone), or (2) dissolution of halite occurring in the rock assemblages of the aerated zone, or in the host aquifer rocks. The dissolution of halite is fast — water coming into contact with it will reach saturation in a few days. Thus, every groundwater has had ample time to reach saturation concentrations of Cl with respect to halite, provided that this mineral occurs in the rocks hosting the water. Hence, groundwater that has a Cl concentration that is distinctly lower than the saturation concentration indicates that (1) halite is missing from the aquifer rocks, and therefore (2) the observed dissolved Cl was brought in by the recharge water, and is thus atmospheric in origin (Mazor and George, 1992, Mazor et al., 1992). The studied artesian groundwaters at Hazeva contain Cl in concentrations of 235–1800 mg l^{-1}. Thus, these waters are by two to three orders of magnitude undersaturated with respect to halite (saturation concentration being more than 200 000 mg l^{-1}) and, hence, the observed Cl is atmospheric.

Competing processes that may produce low Cl groundwater and warrant discussion are discussed below.

(1) Dilution of high Cl water with fresh water, a process that is not feasible in the case of pressurized artesian aquifers.

(2) Residues of seawater are present in the rocks — an explanation that is implausible for groundwaters with Cl concentrations that are one to two orders of magnitude lower than the concentration in seawater.

(3) Halite did occur in the aquifer rocks but in a deficient abundance. This case would necessitate that halite was present in the aquifer rocks in an amount that was 0.1–1% of the amount needed for saturation. This is hard to envisage, as water is flushing through the aquifers in the through-flow model, or it did so in the earlier phreatic stage of the stagnant aquifer model. If halite did exist in the aquifer rocks, it either remained there in appreciable amounts and then the groundwater had to be saturated with respect to halite, which is not the case, or the halite was washed away. An intermediate stage in which just 0.1–1% of the saturation value of halite has been left in the rocks, calls for an extremely high coincidence, which could not have been repeated to produce highly undersaturated groundwaters as observed in several different aquifers in the case study of Hazeva.

(4) Disseminated halite crystals, engulfed by less soluble minerals, exposing the halite for dissolution at a limited rate that is determined by the less soluble minerals of the rock. Such a structure is unknown in permeable rocks such as sand and sandstone which constitute the aquifer rocks in the Hazeva case study. This point was checked even for carbonate rocks in a series of laboratory experiments. Representative samples from the Central Galilee were powdered (grain size greater than 250 μm), put into test tubes with a known volume of water, and placed in a shaker at a temperature of 23 ± 1°C for different periods of time (from 2 h to 130 days). Thus, if halite crystals were present in the rocks, they would be all dissolved. The Cl concentrations obtained in the water were: 30–70 mg l^{-1} (Nadler et al., 1980). These low Cl concentrations characterize the water that is present in the rocks. Similar results were obtained with other types of rocks from the Rift Valley (Mazor et al., 1973).

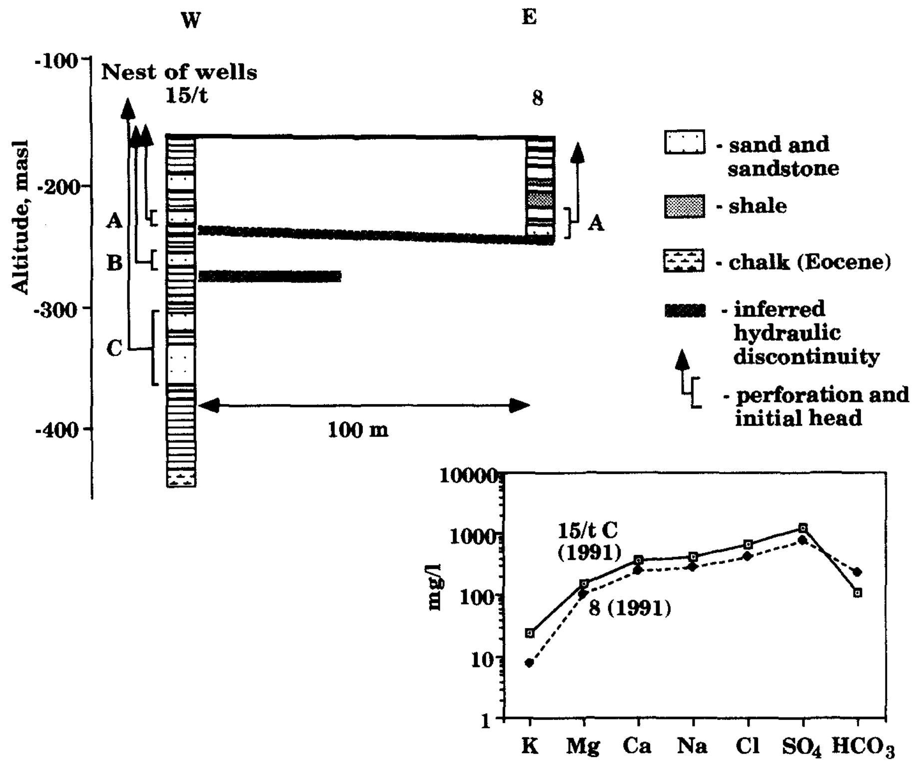
Based on the listed observations it is concluded that the low Cl concentrations observed in the artesian waters of Hazeva indicate the Cl has an external (atmospheric) origin. Processes that determine the concentration of atmospheric Cl in groundwater include: (1) initial concentration in the precipitation, (2) intensity of evapotranspiration, which is determined by the local relief, which in turn, determines retardation of water on the surface (Mazor and George, 1992). The interplay of these processes has led to different Cl concentrations in the recharge water through different parts of the terrain, at present and during different paleo-climate regimes.

The Cl of atmospheric origin provides a useful marker to distinguish aquifers by its concentration in waters tapped in adjacent wells (Mazor and George, 1992; Mazor et al., 1992).

3. Examples of different adjacent artesian aquifers

Evidence for distinct aquifers is given in Fig. 4 which portrays a cross-section through wells 15/t A, B and C (a nest of three adjacent wells, the deepest one drilled down to −440 m.a.s.l., reaching Eocene chalk) and well 8, which is only 100 m distant (drilled to −250 m.a.s.l.). The data, given in the table of Fig. 4, reveal that in well 15/t (1) aquifer C is distinct from aquifer B: the initial hydraulic head was 31 m higher in C, and the dissolved Cl concentrations differed as well, and (2) aquifer B and aquifer A are distinct as their Cl concentrations, observed at the initial stages of abstraction, varied significantly (271 mg l^{-1} in A but 895 mg l^{-1} in B; Fig. 4). Hence, two efficient hydraulic barriers must separate aquifers A, B, and C. Well 8, 100 m away, was terminated in the same aquifer as aquifer A of well 15/t, as revealed from the similar depth, similar rock sequence and similar initial Cl concentration (260 and 271 mg l^{-1} Cl; table in Fig. 4).

Samples from aquifer A in well 8 and from aquifer C in well 15/t revealed no measurable tritium, indicating that the waters predate the nuclear bomb tests, and therefore no bomb-produced ^{14}C is present. The ^{14}C concentrations varied considerably: 58.1 p.m.c. in aquifer A (well 8), and only 1.8 p.m.c. in aquifer C (well 15/t), indicating a significant age difference, the deeper aquifer hosting much older water. The $\delta^{13}C$ values were −8.0 in both aquifers, indicating that the same water–carbonate rock interaction took place. A detailed ^{14}C study conducted in the Judean Mountains (Kroitoru et al., 1989) revealed a similar setup, of no measurable tritium and $\delta^{13}C$ of −8.0‰, an initial ^{14}C value of about 65 p.m.c. (it was deduced that the water–rock interaction was mainly with carbonates but to some degree also with silicates). Hence, the non-measurable tritium and the 58.1 p.m.c. observed in the water of aquifer A indicate an age in the range of 50 (pre-bomb) to 2000 years. The 1.8 p.m.c. observed in the water of aquifer C indicates about five half lives past, i.e. an age of 25 000 years. This is taken as a minimum age as the small measured ^{14}C concentration is within the limit of detection and may stem from contamination. Thus, the age of the water in aquifer C is regarded as more than 25 000 years (and a significantly higher age is possible). This dating information is of considerable importance as it demonstrates that waters in aquifers A and C were efficiently separated for more than 25 000 years. Thus, these two aquifers are not separated by regular aquicludes, that are occasionally slightly leaky, but they are separated by hydraulic discontinuities (layers of extremely low permeability). The Cl concentration in the water extracted from the upper aquifer, A (well 8), nearly doubled during the years of exploitation (Fig. 4), indicating that the well produced more than one type of water, i.e. the respective hydraulic discontinuities were breached owing to the change in the hydraulic head.



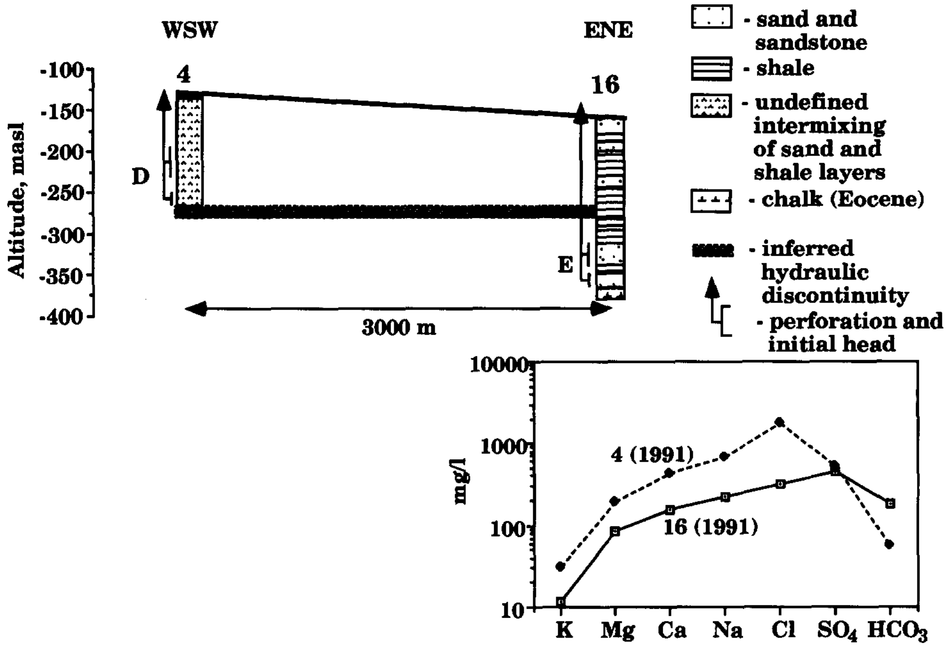
Well, No	Date of drilling	Date	Well top, masl	Head, masl	Perfor., masl	K mg/l	Mg mg/l	Ca mg/l	Na mg/l	Cl mg/l	SO_4 mg/l	HCO_3 mg/l
8	Jun. 72	Dec. 88 July 91	-169	-169.5	-224 to -243	9	100	245	278	260 417	740	220
15/tA	Dec. 71	Dec. 71	-167	-160.1	-211 to -230					271	570	
15/tB	Dec. 71	Dec. 71	-167	-160.1	-257 to -275					895		
15/tC	Dec. 71	Jul. 91	-167	-129.0	-298 to -359	25	147	363	428	680	1225	112

Well, No	Date	^{18}O‰	T, TU	$\delta^{13}C$ ‰	^{14}C pmc	Water age, years*
8	Jul. 91	-4.80	0.4	-8.0	58.1	50 to 2000
15/t C	Jul. 91	-6.2	0.0	-8.0	1.8	>25000

* Applying 65 pmc as initial ^{14}C in the aquifer.

Fig. 4. Data and transact of a nest of wells 15/t and the 100 m distant well 8. Three distinct aquifers A, B, and C, separated by hydraulic discontinuities are defined on the grounds of significant chemical, age and head differences (text).

A second example of the existence of distinct aquifers is given in Fig. 5 which shows a cross-section between wells 16 and 4, which are 3 km apart. Well 16 was drilled to −372 m.a.s.l.; it passed the Shahaq Member at the base of the Hazeva Formation, and possibly reached Eocene chalk (Galai, 1990). Well 4 was drilled to −264 m.a.s.l. and it probably reached the Gidron Member of the upper Hazeva Formation. The data given in the table of Fig. 5 indicate that the hydraulic head in well 4 was 20 m higher than the head in well 16, and hence, water flow could be concluded from the region of



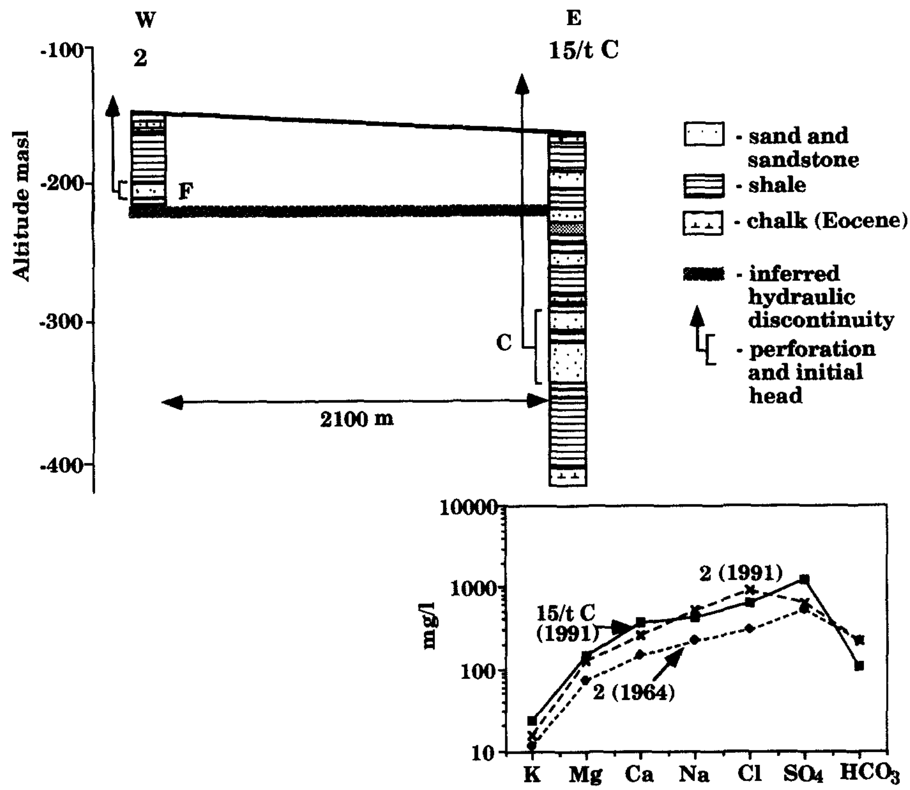
Well, No.	Date of drilling	Date	Well top, masl	Perfor., masl	Head, masl	K mg/l	Mg mg/l	Ca mg/l	Na mg/l	Cl mg/l	SO_4 mg/l	HCO_3 mg/l
4	Sept. 65	Sept. 65 July 91	-129	-197 to -229 -256 to -264	-124.6 -142.5	36 30	255 192	461 430	642 670	1691 1800	1090 520	143 54
16	Aug. 90	Aug. 90 July 91	-161	-325 to -342 -361 to -366	-144.8 -155.0	12	83	161	208	317	510	200

Well, No	Date	^{18}O‰	T, TU	$\delta^{13}C$ ‰	^{14}C pmc	Water age, years*
16	Jul. 91	-5.49	0.1	-6.88	25.5	~7500
4	Jul. 91	-5.84	0.9			

*** Applying 65 pmc as initial ^{14}C in the aquifer.**

Fig. 5. Data and transect of well 4 and the 3 km distant well 16. The very different chemical compositions of the water in these wells indicates they tap two separate artesian aquifers, and the observed head difference constitutes an apparent gradient (text).

well 4 to the region of well 16. However, the Cl concentration in the 'downgradient' well 16 is much lower (by a factor of 4) than the Cl concentration observed in the 'upgradient' well 4, which is impossible because the Cl concentration can not decrease along a flow path. The explanation that the lower Cl concentration in the hypothetical 'downgradient' well is caused by intrusion of a low-Cl water, is not plausible, as the systems are pressurized. Thus, the aquifers tapped in wells 4 and 16 are not connected



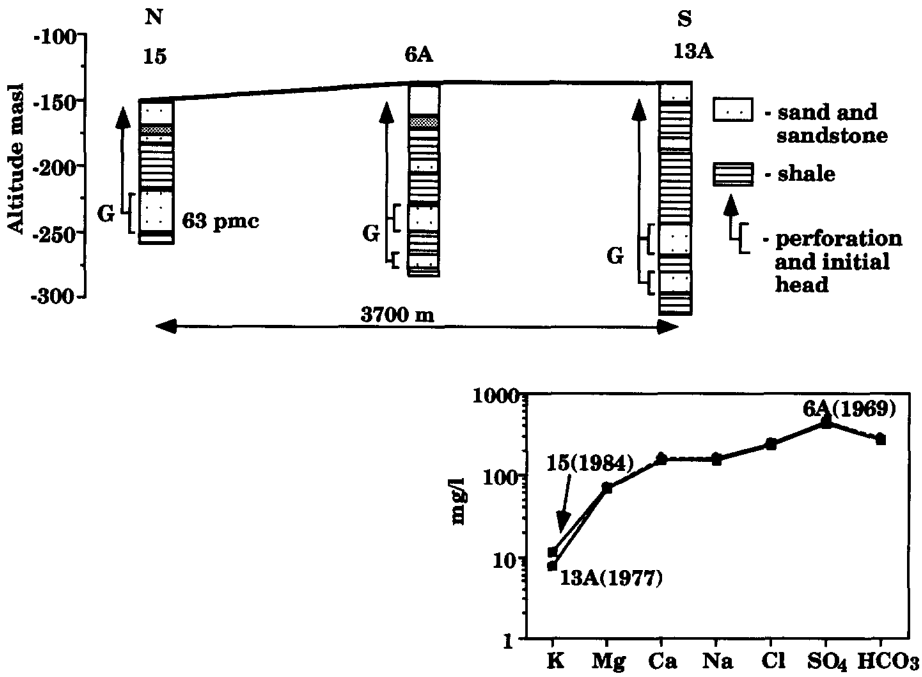
Well, No.	Date of drilling	Date	Well top, masl	Head, masl	Perfor., masl	K mg/l	Mg mg/l	Ca mg/l	Na mg/l	Cl mg/l	SO4 mg/l	HCO3 mg/l
2	Jul. 64	Jul. 64	-148		-200 to -211	11.5	73	146	217	298	523	220
		Jul. 91				15.5	124	253	530	925	650	219
15/t C	Dec. 71	Jul. 91	-167	-129.0	-298 to -359	25	147	363	428	650	1225	112

Well, No.	$\delta^{18}O$‰	T, TU	$\delta^{13}C$‰	^{14}C pmc	Water age, years*
2	-5.4	0.0	-8.1	33.31	~ 5300
15/t C	-6.2	0.0	-8.0	1.8	>25000

* Applying 65 pmc as initial ^{14}C in the aquifer.

Fig. 6. Data and transect of the well nest 15/t and well 2. Another example is seen of waters that differ significantly in their chemical and isotopic composition, age, and heads, indicating the existence of different artesian aquifers, separated by a hydraulic discontinuity.

and they constitute separate aquifers, D and E. This conclusion is supported by the respective Na, Ca, Mg, and SO_4 concentrations that reveal different chemical compositions. Hence (1) the two distinct aquifers are not connected hydraulically, and therefore (2) the head difference between the two aquifers can not be regarded as a hydraulic gradient. If the water composition differences were ignored, one would have deduced an 'apparent hydraulic gradient' between these wells. In this case, too, the pronounced differences in the water chemistries and water heads indicate that the two aquifers are located in different rock units that are hydraulically separated.



Well, No	Date of drilling	Date	Well top, masl	Head, masl	Perfor., mals	K mg/l	Mg mg/l	Ca mg/l	Na mg/l	Cl mg/l	SO_4 mg/l	HCO_3 mg/l
15	Oct. 83	Jan. 84 July 91	-154	-156.7	-216 to- 253	9 8	72 62	154 137	162 162	246 245	448 360	266 185
6 A	July 69	Oct. 69 July 91	-138	-147.2	-223 to -246 -269 to -279	9 9	70 82	158 158	159 172	240 242	443 440	272 249
13 A	June 77	June 77	-136	-146.6	-249 to -267 -276 to -303	8	70	150	150	235	421	265

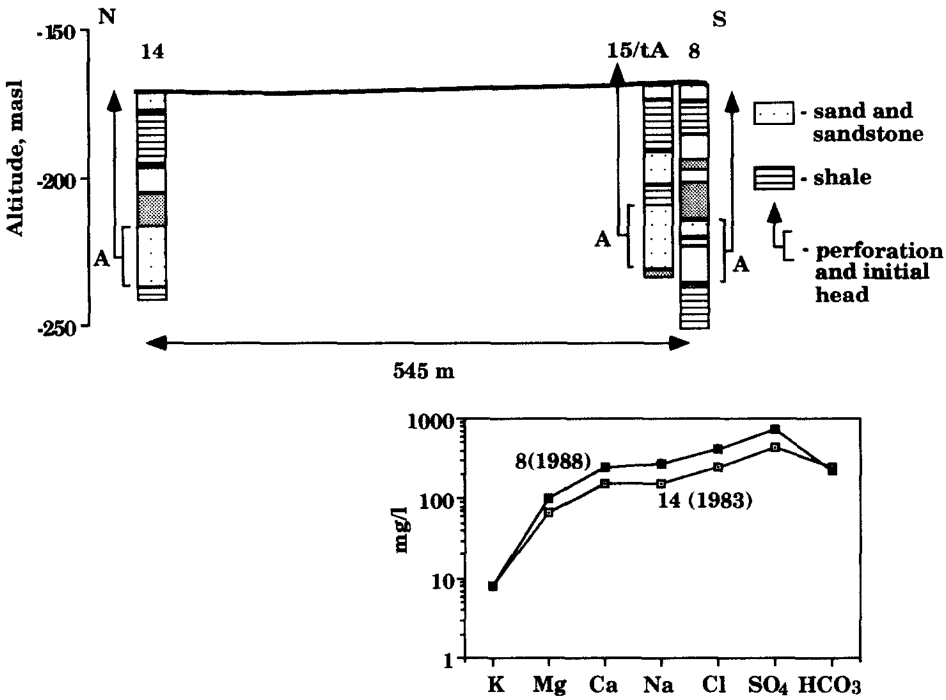
Well, No	Date	^{18}O‰	T, TU	$\delta^{13}C$‰	^{14}C pmc	Water age, years*
15	July 91	-4.83	0.2	-7.8	63	50 to 1000

* Applying 65 pmc as initial ^{14}C in the aquifer.

Fig. 7. Data and transect of three wells that reveal the same composition and seem to tap the same aquifer (text).

Aquifer E of well 16 revealed no measurable tritium and a ^{14}C concentration of 25.5 p.m.c.. This leads, by the above discussed dating considerations to a water age of approximately 7500 years, i.e. an age that differs from the age found for aquifers A (well 8) and C (well 15/t C).

A third example of the existence of distinct aquifers is given in Fig. 6 which presents a transect through wells 2 and 15/t C. Comparison between aquifer F tapped in well 2



Well, No	Date of drilling	Date	Well top, masl	Head, masl	Perfor., masl	K mg/l	Mg mg/l	Ca mg/l	Na mg/l	Cl mg/l	SO4 mg/l	HCO3 mg/l
14	Jul. 83	Nov. 83	-170	-169.7	-220 to -235	8	68	156	154	247	448	249
		Dec. 88				9	161	261	280	508	665	193
8	Jun. 72	Dec. 88	-169	-169.5	-224 to -243	8	118	253	280	260	780	187
		July 91				9	100	245	278	417	740	220
15/tA	Dec. 71	Dec. 71	-167	-160.1	-211 to -230					271	570	

Well, No	Date	^{18}O ‰	T, TU	$\delta^{13}C$ ‰	^{14}C pmc	Water age, years*
8	Jul. 91	-4.80	0.4	-8.0	58.1	50 to 1000

* Applying 65 pmc as initial ^{14}C in the aquifer.

Fig. 8. Data and transect of three wells that had initial Cl concentrations similar to the water found in aquifer G, shown in the previous figure. However, during exploitation the concentrations of dissolved ions increased by a factor of 2, indicating encroachment of water from an adjacent aquifer.

Table 1
Comparison of data of three adjacent wells

Well	Drilling year	Depth (m)	Perforation (m.a.s.l.)	Temp. (°C)	Initial head (m.a.s.l.)	Initial Cl (mg l^{-1})	1990 Cl (mg l^{-1})	^{14}C (p.m.c.)	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
16	1990	211	−385 to −342 −362 to −369	30.1	−151 −144	375	317	25.5	−6.9	−5.23
3	1983	121	−250 to −260	28.7	−143	294	279	36.7	−8.0	−4.96
15	1965	103	−216 to −256	29.0	−157	246	245	63.0	−7.8	−4.83

and aquifer C of well 15/t, reveals that the two differ significantly in their chemical composition, and ^{14}C age, providing another example of distinct pressurized aquifers that are separated by a hydraulic discontinuity. Comparison of the initial (1964) chemical analysis of the shallow aquifer F in well 2 with the 1991 data reveals a distinct change, indicating encroachment of a more saline type of water owing to decrease of hydraulic heads during exploitation.

4. An example of adjacent artesian wells tapping the same aquifer

Wells 15, 6A and 13A are non-flowing artesian, i.e. the water rose in the well after drilling, but did not reach the surface. The water encountered has the same chemical composition, and similar initial heads were observed (Fig. 7). This similarity indicates that these three wells probably tap the same aquifer G, which therefore extends for at least 3.7 km in the north–south direction (Fig. 7). The water of well 15 contained 63 p.m.c., accompanied by no measurable tritium, indicating an age that is pre-1954, but young in ^{14}C terms (50–1000 years). The fact that the water in well 15 was initially pressurized, warrants discussion in light of its young age. Under the present highly

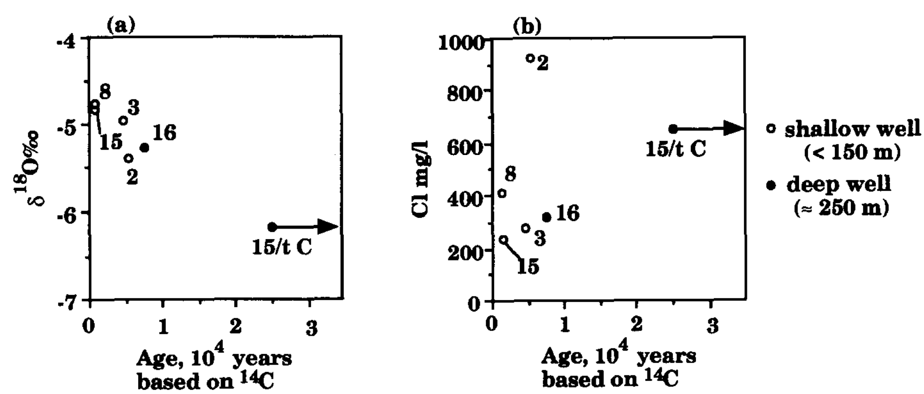


Fig. 9. $\delta^{18}O$ and Cl as a function of ^{14}C derived age (data of 1991). The observed negative $\delta^{18}O$–age correlation indicates recharge during different climatic regimes. The lack of a Cl–age correlation indicates that the observed $\delta^{18}O$–age correlation is not produced by mixings.

arid climate it is plausible that there is no active recharge in the area and, hence, it is more plausible that the observed artesian pressure is caused by compaction, which in turn means entrapment. Thus, we may face a very recent case of groundwater entrapment.

Similar initial ion concentrations found in the shallow pressurized waters tapped in wells 8, 15/tA and 14 (Fig. 8), indicate these wells most probably tap the same aquifer. Furthermore, these wells have compositions that are similar to the compositions found in wells 15, 6A and 13A (Fig. 7). Thus, there is a possibility that the two groups of wells tap the same aquifer of fresh and relatively young water, i.e. aquifer

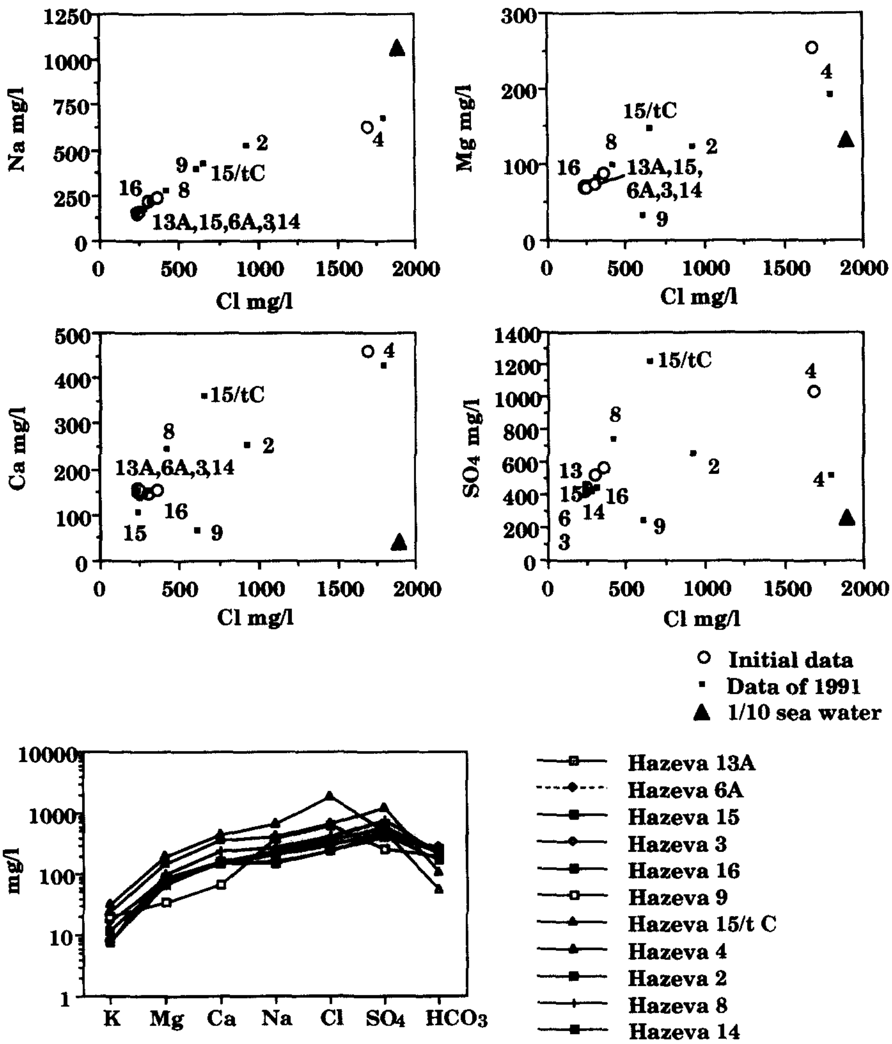


Fig. 10. Chemical composition of the wells studied, revealing the existence of different water types, i.e. different aquifers. The composition of these waters differs significantly from the composition of seawater, indicating that no seawater leftovers are involved.

A might be the northern extension of aquifer G. If this is the case then the aquifer extends for over 8 km in the north–south direction (Fig. 3).

Well 3, situated only 1 km west of well 15 (Fig. 3), is perforated at almost the same depth, and the temperature, Cl concentration and $\delta^{13}C$ and $\delta^{18}O$ values were similar (Table 1). Yet, the initial heads and especially the ^{14}C values differed significantly (Table 1). Hence, it seems that well 3 tapped an aquifer that is hydraulically separated from well 15.

5. Isotopic indications for recharge under different paleo-climate regimes

An interesting pattern is seen in Fig. 9: older waters are isotopically lighter, a trend often observed in paleo-waters. The negative linear correlation seen in Fig. 9(a) between

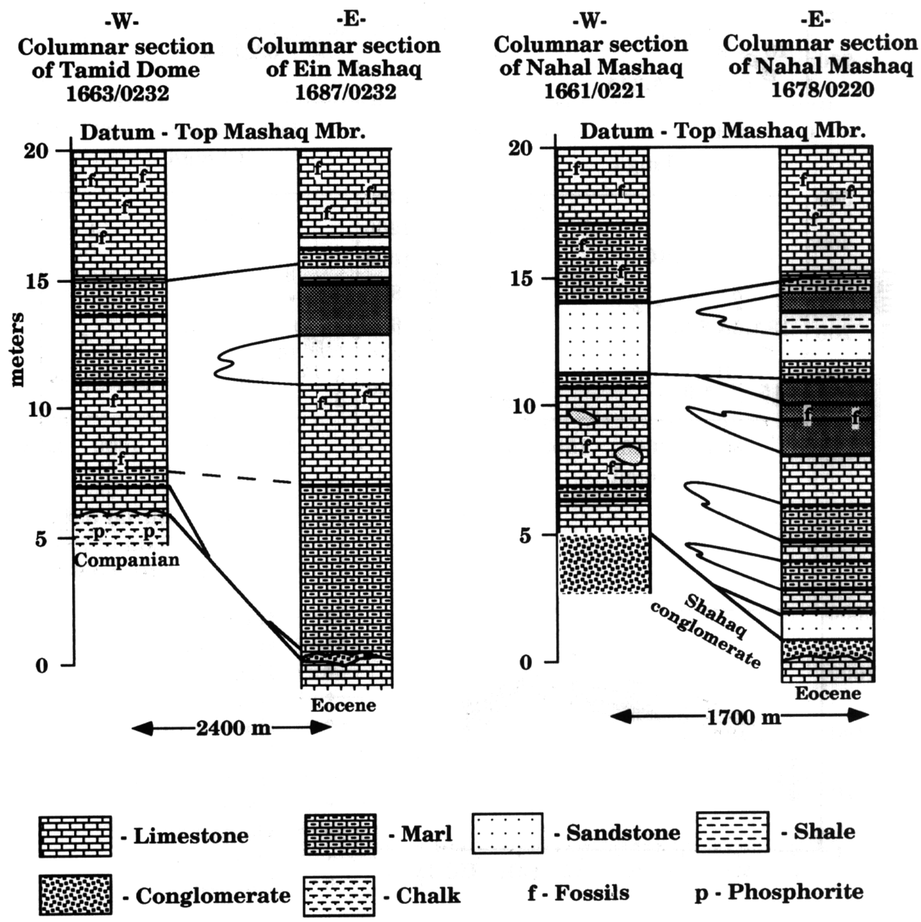


Fig. 11. Facies changes in the Mashaq Member of the Hazeva Formation (redrawn after Sneh, 1981) as an example of the frequent lateral lithological changes of the rocks hosting the artesian waters.

$\delta^{18}O$ and the age may be either the result of mixing of two waters, or an indication of a colder paleo-climate. However, no correlation is observed between the Cl concentration and the age (Fig. 9(b)), indicating that we are not dealing with mixings. Thus, the individual aquifers in the part of the Arava segment of the Rift Valley studied were recharged and sealed at different times, under changing climatic conditions.

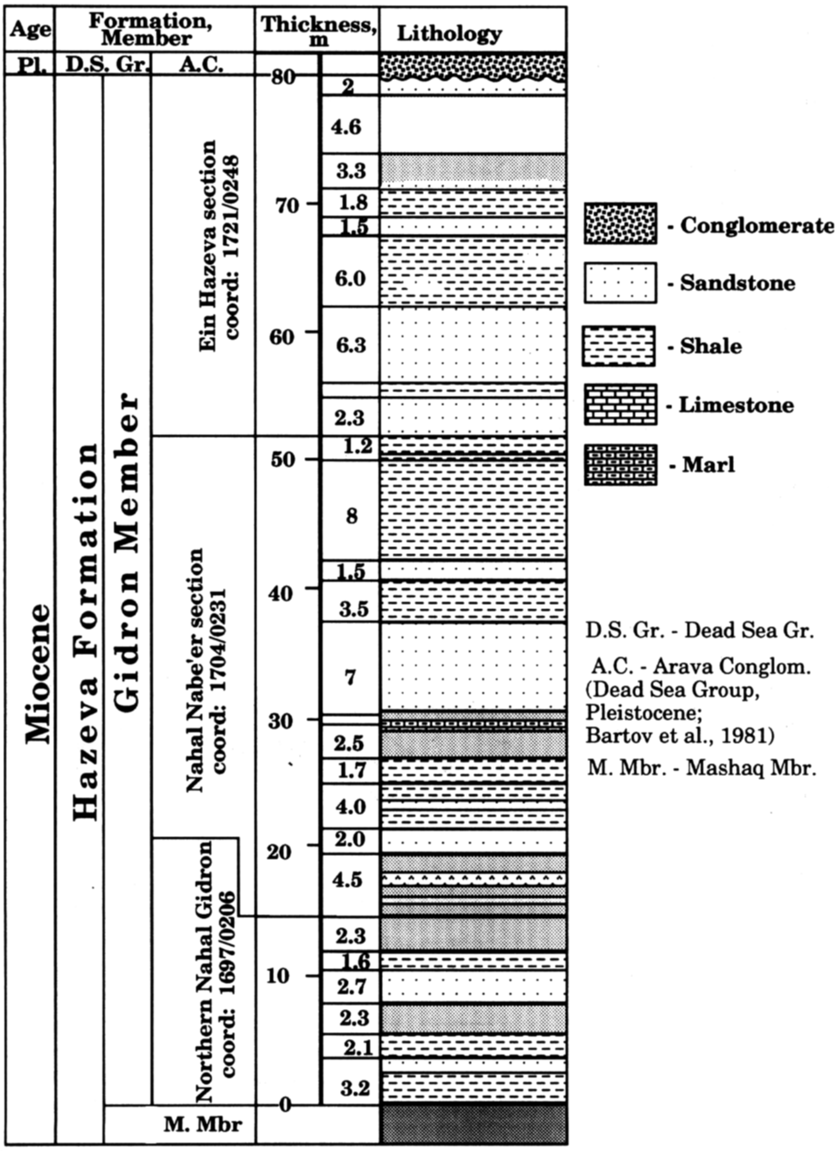


Fig. 12. A composite section through the Gidron Member of the Hazeva Formation (redrawn after Sneh, 1981), demonstrating the frequent alternations of sandstone and shale lenses hosting the stagnant artesian aquifers studied.

6. Chemical diversity revealing several different artesian aquifers in the 50 km^2 study area

The chemical composition of the 11 artesian wells studied reveals: (1) the existence of aquifers with significantly different compositions (Fig. 10); (2) a composition that is significantly different from seawater (triangle), indicating that no seawater leftovers are present. At least six different aquifers (A–F) are recognized in the 50km^2 study area, and a larger number may be found when additional wells are drilled.

Three springs issuing along the Rift Valley rims near the Hazeva area have compositions (Yechieli, 1987) that differ from those of the waters encountered in the wells studied. The Gidron Spring contains 900 mg Cl l^{-1}, the Tamid Spring contains 1100 mg Cl l^{-1} and the Sach Spring contains 1900 mg Cl l^{-1}. No hydraulic interconnections seem to exist between the stagnant artesian aquifers and the aquifers feeding the more saline springs.

7. The model of stagnant pressurized aquifers

The Hazeva Formation rocks, which comprise the part of the Rift Valley studied, occur as lenses and interfingering structures, stacked one upon the other, accompanied by frequent lateral facies changes (Fig. 11). Most sediments are continental, mainly sandstone, shale, and conglomerate (Fig. 12). As these rocks were accumulated in the subsiding rift, the permeable rocks exposed on the surface operated temporarily as through-flow phreatic aquifers. As subsidence and sediment

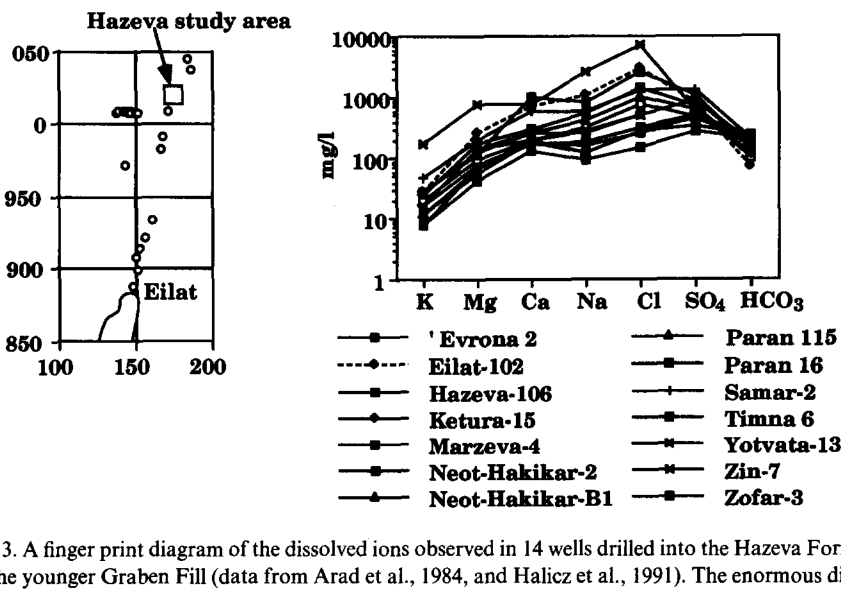


Fig. 13. A finger print diagram of the dissolved ions observed in 14 wells drilled into the Hazeva Formation and the younger Graben Fill (data from Arad et al., 1984, and Halicz et al., 1991). The enormous diversity observed in the groundwater compositions indicates the presence of a multitude of distinct aquifers in this section of the Rift Valley.

accumulation continued, each phreatic aquifer was in turn covered by younger layers of impermeable and permeable rocks, the latter constituting new through-flow phreatic aquifers. The buried aquifers were sealed from further recharge and discharge and were turned into stagnant aquifers, as visualized in Fig. 2. The buried stagnant aquifers became pressurized by lithological compaction. When a pressurized aquifer is tapped by a well that flows freely or is pumped, the water flows by release of compressibility and is further 'squeezed out' as long as compaction effectively continues. According to the present working hypothesis the age of the trapped groundwaters is expected to be older in the deeper aquifers, as is observed.

The conclusion that the Rift Valley rocks constitute a large variety of distinct aquifers, hosting groundwaters of different chemical compositions, holds true for a larger part of the Arava Rift Valley as shown in Fig. 13.

8. First principle considerations in favor of the stagnant aquifer model of the artesian systems studied

Artesian systems are traditionally envisaged as dynamic aquifers with recharge in an outcrop section, through-flow, and discharge 'somewhere' in a downflow direction. The following observations oppose this model for the wells studied:

(1) Real and apparent hydraulic head gradients. According to the through-flow model, hydraulic heads observed to descend between artesian wells in a given direction, indicate through-flow along that direction. This hydraulic reasoning is based on the assumption that hydraulic continuity exists between the rock zones tapped by the wells that supplied the applied hydraulic head data. The head difference between wells that can be demonstrated to tap hydraulically interconnected rock bodies constitutes a 'real hydraulic head gradient'. However, as shown above for the Hazeva area, groundwater properties occasionally indicate that aquifers tapped by adjacent artesian wells are hydraulically disconnected and through-flow does not occur in spite of observed hydraulic head differences. The hydraulic head differences in such cases constitute an 'apparent hydraulic head gradient'. The through-flow model of the artesian system in the northern Arava Valley implies that the water is discharged into the Dead Sea Basin. Accordingly, a northward hydraulic head gradient should be observed in the artesian wells of the Hazeva region, but this is not the case. The initial hydraulic heads, measured in the wells studied, are seen in Fig. 14 to go in all directions with no preferred pattern, opposing the through-flow model and in line with the model of several stagnant aquifers, buried at different depths, and hydraulically isolated from each other.

(2) Limited precipitation. The study area and its surroundings have an arid climate, with an average annual rainfall of 50 mm, and the weather is hot and dry almost all the year around. Flood events are scarce and limited to a few hours. Present recharge is observed to be nil, a conclusion supported by the lack of observed phreatic water in the area.

(3) The broken funnel effect. Local recharge can be ruled out as the system is confined. This leaves as an open possibility recharge through outcrops in remote

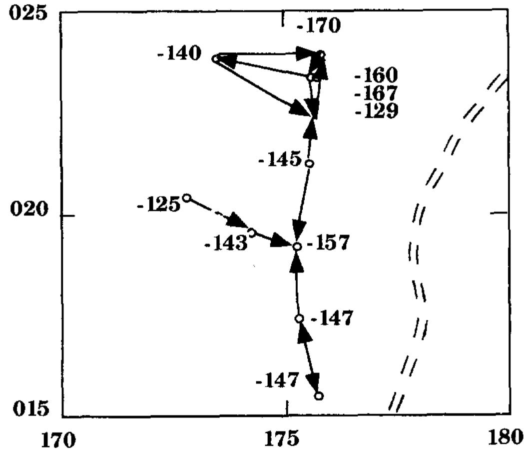


Fig. 14. Hydraulic heads measured in the studied artesian Hazeva wells (Fig. 3) at the time of their completion. Arrows point in the direction of groundwater flow as would be deduced from hydraulic head data alone, but the arrows (a) mark apparent hydraulic heads as revealed from the properties of the water in the adjacent wells (text), and (b) mark no northward gradient, ruling out general underground discharge into the Dead Sea Basin.

areas. However, the host rocks of the Hazeva Formation are absent outside the Rift Valley in the study area, and thus remote recharge would be from outcrops of rocks of other formations, e.g. Cenomanian to Senonian rocks. The passage of recharge water from the outcrops in the mountains into the different aquifers identified in the rift-filling sediments is not easily explained. By analogy, this resembles filling of a pipeline through a funnel — the funnel must be tightly connected to the pipeline. However, the contacts of the rock beds outside the Rift Valley to the Hazeva Formation rock lenses inside the Rift Valley is through the highly fractured Rift Valley fault zone. Hence, the funnel is broken in this case, and groundwater flowing from aquifers in the mountainous areas flanking the Rift Valley would not be directed into a specific artesian aquifer in a rock lens in the valley. It would flow all over.

(4) The layered cake and the multifunnel requirement. The rock section in the segment of the Rift Valley studied has been shown to constitute an assemblage of overlying aquifers and aquicludes, resembling a layered cake. As discussed above, each aquifer has its own concentration of Cl and of other ions, and its specific water age, indicating recharge from different terrains under different climates. The recharge intake funnel model, discussed above for the through-flow model, is further complicated in light of the layered cake requirement. Not one intake funnel system is accordingly required but a multifunnel system, each funnel feeding a separate aquifer with a different water composition. The multifunnel requirement is not fulfilled, as the field data reveal, and the recharge mechanism, essential for the through-flow model, does not exist. Isolated stagnant aquifers seem more plausible at least for some of the artesian waters of the Rift Valley.

(5) The lithological heterogeneity effect. The Rift Valley contains mainly continental sediments, highly variable vertically and laterally, and with lens

structures, interfingering, and facies changes. This lithological heterogeneity indicates the presence of a multitude of potential groundwater traps and nothing like large-scale continuous rock beds, required for the dynamic through-flow model.

(6) The paleo-climatic recharge observation. As shown in the discussion of the ^{18}O data (Fig. 9), the groundwaters encountered in the study area were recharged during different climatic regimes, assigning each aquifer a different age of recharge, and indicating that aquifers are distinct and hydraulically isolated.

9. An aquifer management problem

The present study was initiated owing to a management problem. In 1990 well 16 was drilled and pumping was commenced. Owners of neighboring wells questioned whether the new well drew water from the aquifers that sustain previously drilled wells, in particular the 2 km distant wells 3 and 15 (Fig. 3). The following observations indicate that low-permeability material separates the three named wells (Table 1): (1) well 16 taps two sandy beds (Fig. 5) and is distinctly deeper than wells 3 and 15, (2) the initial head of well 16 was similar to the head in well 3, but significantly different from that of well 15 (Table 1), (3) the Cl concentration differs slightly between the three wells, (4) the ^{14}C concentration differs in the three wells, well 16 taping the oldest water, (5) the $\delta^{13}C$ value of well 16 is distinctly more positive than the value in the other two wells, possibly reflecting recharge during a more arid or colder climate, (6) the $\delta^{18}O$ values differ as well, (7) the temperature differs slightly, well 16 having the highest temperature, in good agreement with its greater depth, and (8) the hydraulic head in well 3 revealed fluctuations around −150 m.a.s.l. and this trend did not change after well 16 was operated, and the hydraulic head of well 15 was −157 in 1984 and it dropped to −163 in 1990, but no change was observed after well 16 was operated.

The conclusion from the above observations is that the two sandy beds pumped in well 16 are efficiently separated from the shallower aquifers exploited in wells 3 and 15. Hence, the exploitation of water from well 16 is independent from that of the adjacent wells.

10. Conclusions

(1) The term 'Hazeva Formation aquifer', commonly used, should be avoided as: (a) the Hazeva Formation includes numerous overlying permeable and impermeable rock lenses, constituting a potential sequence of individual aquifers, aquicludes, and layers of very low permeability, (b) the Hazeva Formation occurs in different regions that are separated by a deep relief, constituting non-connected groundwater systems. These arguments hold true everywhere: stratigraphical terms should not be misused as hydraulic terms (Mazor et al., 1992).

(2) An aquifer should be defined not only on the grounds of lithological data but also on the grounds of water properties, e.g. heads, temperatures, chemical and

isotopic composition, and concentration of age indicators. Similar water properties observed in adjacent wells indicate that it is feasible that the respective wells reach the same aquifer and that they are likely to be hydraulically interconnected. Significant differences in water properties in adjacent wells establish that these wells tap different aquifers. Thus, the properties of groundwaters encountered in artesian wells provide a method to map the spatial extension of individual aquifers.

(3) As the artesian aquifers studied are found to be sealed off from any recharge and discharge, they are stagnant aquifers, i.e. with no groundwater through-flow. The hydrological implication of the lack of through-flow is that the observed hydraulic heads do not stem from the hydraulic head in a connected phreatic aquifer (Fig. 2), but the observed hydraulic heads originate from lithological compaction of the host rocks. In this context it is advisable to apply the term real hydraulic gradient for gradients based on wells that are proven to be hydraulically interconnected, and apparent hydraulic gradient for gradients based on data from wells that tap different aquifers. Previous researchers suggested that the groundwater in the already criticized 'Hazeva Formation aquifer' flows northward and is drained into the Dead Sea Basin — it is suggested that this was based on a misinterpretation of apparent hydraulic gradients.

(4) The establishment of the existence of stagnant pressurized aquifers is interesting scientifically, and has far reaching practical implications, as precious water reservoirs that are immune to contamination, and as potential high-quality waste repositories in the case of artesian aquifers that have been depressurized as a result of exploitation.

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