Hydrogeological insights in antiquity as indicated by Canaanite and Israelite water systems

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1. Introduction

Ancient cities that were built on hilltops for defensive advantages suffered from the disadvantage that their natural water sources (e.g. springs and wadi floods) were outside the settlement – a fatal weakness at a time of siege. As rain seldom falls in the Near East between the months of April and October, a permanent connection to the nearby water supply is a matter of survival. This required the inhabitants either to dig wells into the aquifer under the settlement, or to establish an underground connection to a water source outside the city. Such water systems were a typical element in the defenses of Canaanite and Israelite cities of the Bronze and Iron ages (ca 3300–586 B.C.E.).

Water systems have been found in many sites in Israel (Fig. 1; Inset A), each displaying different hydrogeological conditions. In several of these sites, however, constructing water systems required engineering knowledge only. In all water systems in the City of David, in Jerusalem (Reich and Shukron, 2004; Shiloh, 1992; Gill, 1991; Frumkin et al., 2003; Frumkin and Shimron, 2006) and in Megiddo (Lamon, 1935), the engineering mission was to connect the cities with outside springs via shafts and tunnels; hydrogeological considerations were hardly involved. In Gibeon (Pritchard, 1961), the tunnel dug at the bottom of the “pool” was unequivocally directed to reach a spring, not the groundwater, which was encountered a few meters from the spring (Cole, 1980). In Gezer – where dating is controversial (Macalister, 1912; Yadin, 1969; Dever, 1965) – the tunnel reached groundwater collected in a natural cave, which might has a connection outside the mound (Reich and Shukron, 2003) (Fig. 2b). In the Canaanite city of Arad (Amiran et al., 1985), the construction constitutes a well-like cistern and not water well; groundwater table here is tens of meters below the bottom of the cistern (Fig. 2e).

In other sites, though, hydrogeological considerations were essential in the construction of the water systems. The purpose of this study is to analyze these conditions, evaluate the degree of success in finding water and thereby assess to what extent the concept of local and regional groundwater table in the Near East had been mastered during the Bronze and Iron ages.

2. Water search along the coatal plains and stream banks

In sites located close to the Mediterranean Sea shore, e.g. Tel Nami (Artzy, 1991) or Tel Gerisa (Tsuk and Herzog, 1992) (Fig. 2a), where the groundwater table is only several meters below the surface and the host rock is highly permeable sandstone, the ancient engineers possessed the knowledge of how to reach the groundwater since the Neolithic time (Galili and Nir, 1993). The same holds for wells that were dug in or along stream banks where floods...
recharge the shallow gravel aquifers and water can infiltrate through porous sandstone banks, e.g. in Tel Haror (Oren et al., 1991) (Fig. 2d).

The two water wells, dug in Lachish and Beer Sheba, are suggestive of limited understanding of hydrogeological systems more complicated than those described above. At Lachish, a 44 m deep well was dug at the lowest point on the mound's surface (Tufnell, 1953; Ussishkin, 1982), presumably intended to reach the groundwater table in the gravel aquifer of the Lachish Creek running along the foot of the mound. Some water was indeed reported to be found at the base of the cleaned up well. However, the well traversed and bottomed in Oligocene limestone and Eocene barely permeable chalk with no connection to the gravel aquifer and therefore yielded insignificant quantities of water (Fig. 2c). A similar scenario is found at Tel Beer Sheba (Herzog, 2002), where flash floods occur in the nearby Beer Sheba Creek several times every winter. Apparently, the intention of digging the 69 m deep well at this site was to reach groundwater table in the wadi (creek) gravel bed, assuming that it would be stretching laterally under the mound, but the well penetrated mostly through Maastrichtian scarcely permeable chalk (Fig. 2f) which could hardly let through significant quantities of water.

3. The water system of Tel Hazor

The underground water system of Hazor, northern Israel (Shiloh, 1992; Yadin, 1969; Garfinkel and Greenberg, 1997) (Fig. 1), is an eloquent example of Iron-Age system serving an urban community. In 2005, Tel Hazor and its water system were declared a UNESCO world heritage site. As it is a system successfully hewn down to the groundwater table, unconnected to any outside spring, the following inevitable question has to be answered: was this an expression of a profound hydrogeological insight or merely an accidental success? In order to fathom this dilemma, an inquiry into the archeological as well as into the geological and hydrogeological factors had been carried out.

![Fig. 1. A geological map of Tel Hazor.](image-url)
Fig. 2. Water systems in principal sites in Israel (from north to south): (a) Tell Gerisa’s well (Middle Bronze Age) (Tsuk and Herzog, 1992). The shallow regional water table is about 6 m above m.s.l. (b) Tell Gezer’s water chamber, which is a natural cave (Macalister, 1912; Reich and Shukron, 2003) at the contact between the impermeable Paleocene marl and the fractured Eocene chalk. Several springs flow along this contact; the closest, Ein Shusha, is projected onto the section. (c) The well of Lachish dated to stratum IV (Iron-Age II) or earlier (Ussishkin, 1982). The bottom of the well reached the level of Lachish Creek at the foot of the mound, suggesting that the intention was to reach its gravel aquifer. (d) The well of Tell Haror dug above the northern bank of Gerar Creek (Oren et al., 1991) in permeable calcarous sandstone and reached the groundwater table. (e) The well-like cistern of Arad is located at the center of the depression within the walled area of the Early Bronze II city (Amiran et al., 1985). It was hewn into impermeable Eocene chalks to a depth of about 20 m. The groundwater table at this locality is tens of meters below this level and there are no gravel aquifers or springs around. (f) The well in Beer Sheba (see text for details).
3.1. Description of the Hazor’s water system

The water system was discovered by Yadin’s 1968–1969 expedition (Yadin, 1969; Garfinkel and Greenberg, 1997). It is located in the upper city, adjacent to and within the city walls in area L (Fig. 1). Across from the location at the southern foot of the mound in Hazor Creek, an aerial distance of approximately 150 m and an altitude of 195 m above m.s.l., natural springs abound to this very day. The water system includes four elements (Shiloh, 1992; Yadin, 1969; Garfinkel and Greenberg, 1997): entrance structure, vertical shaft, sloping tunnel, and water chamber (Fig. 1; insets B and C). The entrance structure includes two sloping ramps, connecting the occupation level of the Israelite city at an altitude of 228 m above m.s.l. with the head of the stairway of the vertical shaft. The shaft is of trapezoid cross section, roughly 16 × 13 m, narrowing slightly with depth. Its upper part cuts through archaeological remains, belonging to stratum X [10th century B.C.E.; (Yadin, 1969; Ben-Tor, 1983)]; its lower part is quarried in bedrock conglomerate and chalk. The shaft is 19 m deep, and required the removal of approximately 6000 tons of debris and rocks. Five flights of stairs descend around the shaft’s walls, the lowest along the southern wall of the shaft, turning at altitude 202 m above m.s.l. into the sloping tunnel. The tunnel runs straight for 25 m west-southwest, descending about 10 m and terminates into a 5 × 5 × 5 m chamber whose bottom is covered with fresh water, forming a shallow pool at 36 m below the level of the entrance structure (192 m above m.s.l.). The system allowed simultaneous movement of water carriers, people as well as beasts going down or up. The entire water system lies within the perimeter of the mound, providing the inhabitants of Hazor with a convenient approach to water during times of peace, and, more important, at times of siege. Construction of the water system is coeval with stratum VIII, dated to the 9th century B.C.E. and went out of use with the destruction of Hazor by the Assyrian conquest (stratum V) in 732 B.C.E. (Yadin, 1972; Ben-Tor, 1993). It might have been damaged already by the 8th century B.C.E. earthquake (Amos 1:1), documented by destruction in stratum VI (Yadin, 1972).

Yadin (1969, 1972) attributed considerable importance to the fact that the sloping tunnel runs west-southwest, while the Hazor springs are located at the foot of Tel Hazor to the south: “The direction of the tunnel came as a surprise, since we expected to find it to the south, in the general direction of the springs. However, the deliberate and planned position and direction of the tunnel indicates that the engineers possessed sound geological knowledge. It is obvious that they anticipated encountering the water-level – the same as that of the springs – even within the perimeter of the mound” (Yadin, 1969).

The idea that the 9th century B.C.E. engineers planned to encounter the groundwater table within the perimeter of the mound is quite striking, mainly in light of the present knowledge of the hydrogeology of Hazor and its vicinity; the regional aquifer in this area is tens of meters below the spring’s altitude. The uppermost part of the water system is 10 m higher than the lowest point within the 9th century fortifications of the city (Fig. 1). If the ancient engineers dug towards the aquifer, why did they not locate the vertical shaft at the lowest (space-free) point on the mound and by that saved much work and time? Hence, the location of the shaft close to the southern edge of the mound, at closest proximity to the springs, was clearly intentional.

3.2. Geologic setting of Tel Hazor

Tel Hazor is situated on the western margin of the Hula Valley, a large meridional depression along the segmented Dead Sea Fault (DSF). The DSF is an intracontinental left-lateral transform accommodating the relative motion between the African (Sinai) and Arabian plates. It is commonly agreed that the Hula Valley is a rhomb-shaped graben, which subsided in stages during the last 4 Ma (Garfunkel, 1981; Heimann, 1990). The Hula basin is bounded by two longitudinal north-trending en-echelon strands of the DSF, known as the Hula Eastern Border Fault and Hula Western Border Faults (HWBF), which are strongly expressed in the present-day morphology. Transverse faults mark the northern and southern edges of the basin (Heimann, 1990; Rybakov et al., 2003), but their surface expression is subdued and secondary (Sneh and Weinberger, 2003a). A NNW-trending through-going left-lateral strike-slip fault developed diagonally across the basin during the mid-Pleistocene (Schattner and Weinberger, 2008). Consequently, subsidence has been controlled by both the basin bordering faults and the diagonal fault, while the vertical displacement across the transverse faults is minor. The Galilee Mountains rise steeply west of the HWBF. The surface trace of the fault is usually masked by Pleistocene to recent sediments.

Tel Hazor is a man-made occupational mound. Its principal area overlies a natural hill rising 25–35 m above its surroundings. The northwestern edge of the hill is built of the Dalton Basalt, dated to 1.7 Ma (Heimann, 1990). The rest of the hill consists of horizontal beds of conglomerate and chalk of the Plio–Pleistocene Hazor–Gadot Formation, which was deposited contemporaneous with or later than the Dalton Basalt. The conglomerate beds consist of limestone, dolomite and flint pebbles derived from Cretaceous to Eocene formations, and Plio-Pleistocene basalt pebbles derived from the Dalton Basalt. The lower part of the vertical shaft, sloping tunnel and water chamber are cut into 30 m of the Hazor–Gadot Formation.
In the course of geological mapping and delineation of the different segments of the DSF system in and around the Hula Valley (Sneh and Weinberger, 2003b, 2006), we noticed that the Dalton Basalt is faulted against the Hazor–Gadot Formation by the HBWF at the northern foot of Tel Hazor (Fig. 1). Another strand of the fault was delineated at the southern foot of the mound at the Hazor springs. The fault appears to cross the hill of Tel Hazor through area L. Therefore, we resurveyed the shaft, the sloping tunnel and the water chamber. The fault trace was not identified in strata of the shaft and sloping tunnel, which are almost undisturbed beds of conglomerate and chalk. However, these beds are intensively fractured in the water chamber, forming a series of sub-vertical faults (Figs. 3 and 4). The western wall of the water chamber appears to coincide with a fault face (Fig. 4; Fault D) and fault traces on the southern wall are asposed to faults on the northern wall. The easternmost fault (Figs. 3 and 4; Fault A) is the most prominent, throwing a relatively thick conglomerate bed against a set of thin chalk beds. Oblique striae observed along the plane of Fault A, together with the stratigraphy, indicate an oblique left-lateral and normal displacement along this fault. The fault zone is characterized by a smearing of clay and a strong foliation. The strikes of the fault strands are between 355° and 10°, similar to the overall strike of the HWBF.

3.3. Hydrogeological setting of Tel Hazor

To evaluate the influence of the faulting on groundwater flow into the water chamber, we checked it within the framework of the regional hydrogeological trends (Fig. 5). This shows that many springs are aligned along the HWBF, where the permeable Cretaceous to Eocene rocks of the Galilee Mountains are faulted against impermeable Plio-Pleistocene lacustrine and alluvial sediments of the Hula Valley (Grossowicz, 1969; Michelson and Goldstoff, 1974). Among these are the copious ‘Enan springs, as well as the springs of Teo, Hur, and Gome. The now established continuation of this fault further to the south reveals that the Hazor springs are also aligned along this fault. Intake area for these springs is the Galilee Mountains, whence groundwater flows eastward towards the Hula depression, emerging upward along the HWBF (Grossowicz, 1969; Michelson and Goldstoff, 1974).

A two-dimensional numerical simulation was made of groundwater flow along a WSW–ENE cross section through Tel Hazor and its fault zone. The cross section traces the boundary between the Kinneret and the ‘Enan groundwater basins (Fig. 5) and hence is parallel to a flow line, justifying the two-dimensional approach. Along this boundary, groundwater flows through the Judea aquifer from the recharge area at upper Amud Creek east-northeastward and discharges along the HWBF (Fig. 6).

It was assumed that the present-day hydraulic head is roughly the same as at the time of the waterworks construction during the 9th century B.C.E. Paleoclimate studies in central Israel show that the annual precipitation at that time was similar (within ±10%) to
Noticeably, present-day low flux of water in Hazor spring is affected by the pumping of fresh water in boreholes.

We solved the flow equation derived from Darcy’s law and the conservation of fluid mass along a cross section starting with the Galilean groundwater divide between the Mediterranean Sea and the Hula Valley at the west, and Tel Hazor at the east (see Appendix). The hydrological parameters of all lithological units are given in Table 1. The top of the impermeable Cretaceous Lower Judea Group is assigned as the bottom boundary with no flow (Fig. 7). Two vertical boundaries are also assigned with no flow conditions: the western boundary, which is the Galilean water divide, and the impermeable lithological units east of the HWBF. The first 2 km west of the water divide are assigned a constant hydraulic head as measured in boreholes. No recharge is assigned to the rest of the top boundary but discharge is allowed. The results show that the hydraulic head decreases from the western boundary eastward to the point of issue at Tel Hazor (Fig. 8). The simulations show that groundwater ascends along the HWBF into the mound, as well as discharges in local springs (Fig. 8; inset).

4. Synthesis

Based on the delineated fault strands and on the hydrogeological analysis, we suggest an explanation for the construction of the underground water system of Hazor. The water system and its vertical shaft were located in the southern part of the mound due to its close proximity to the nearby Hazor springs. In this it is similar to other water systems in the Iron-Age in Israel, which were located as close as possible to the nearby water source at the foot of the mound (Lamon, 1935; Pritchard, 1961; Herzog, 2002). At an altitude of about 202 m above m.s.l, the sloping tunnel was

Table 1

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Horizontal Permeability (m²)</th>
<th>Vertical Permeability (m²)</th>
<th>Porosity (%)</th>
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<tr>
<td>Judea Group</td>
<td>Limestone, dolostone</td>
<td>$5 \times 10^{-13}$</td>
<td>$5 \times 10^{-15}$</td>
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<tr>
<td>Mt. Scopus Group</td>
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<td>$10^{-19}$</td>
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<td>Avedat Group</td>
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<td>$3 \times 10^{-15}$</td>
<td>10</td>
</tr>
<tr>
<td>Hazor–Gadot Formation</td>
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<tr>
<td>Fault zone</td>
<td>Gravel</td>
<td>$10^{-12}$</td>
<td>$10^{-14}$</td>
<td>10</td>
</tr>
</tbody>
</table>

* Hydrologic properties of Judea Group, which is the main aquifer where flow occurs, are based on pumping tests (Michelson and Goldstoff, 1974). Hydrologic properties of the rest of the units are based on their lithology (Freeze and Cherry, 1979).
constructed in a west-southwest direction sub-parallel to the walls of the city. This direction was apparently chosen to avoid digging too close to the outer face of the mound, notwithstanding the greater distance. A horizontal tunnel should have been designed to connect the end of the sloping tunnel with the springs. However, groundwater was encountered when they reached the fault zone at approximate 195 m above m.s.l. and such a tunnel became redundant. The water chamber was set up exactly along this zone, utilizing the westernmost fault plane as the edge of the chamber. It is also possible that during progressive quarrying of the sloping tunnel, water began to drip from the bedrock as a result of ascending pressurized groundwater along the HWBF and subsequent lateral flow along porous conglomerate beds (Fig. 6 and 8).

Acknowledgments

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Appendix

The flow equation derived from Darcy’s law and the conservation of fluid mass were solved along a cross section starting with the groundwater divide between the Mediterranean Sea and the Hula Valley at the west, and Tel Hazor at the east (Fig. 5). The flow equation and the conservation of fluid mass is (Bear, 1972):

$$\nabla \cdot [\mathbf{K} \nabla h] = \frac{S_s \partial h}{\partial t}$$

(1)

where $\mathbf{K}$ is the hydraulic conductivity tensor ($L T^{-1}$), $h$ is the hydraulic head ($L$), and $S_s$ is the specific storage coefficient ($L^{-1}$). Eq. (1) is solved using CPFLOW, a Galerkin finite element technique with linear shape functions applied over triangular elements for a two-dimensional cross section (Raffensperger, 1996). The top
boundary is a free surface that represents the groundwater table (pressure $= 0$) and its position is calculated at every time step (Neuman and Witherspoon, 1971). Because the groundwater table position is changing in a stationary Cartesian coordinate plane (Eulerian formulation), it is necessary to describe the position of the groundwater table within the elements. Every element is numerically integrated over seven Gauss points at which the pressure is calculated to find the actual position of the groundwater table.

**References**


