CAVES AND KARST HYDROGEOLOGY OF JERUSALEM, ISRAEL

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The city of Jerusalem, Israel, is growing for ~4,000 years on karst terrain. Lacking closed depressions, surface topography seems fluvial, but karst is well demonstrated by speleology and subsurface hydrology. Several caves in the city were truncated by construction works, including an 800 m long river cave (longest limestone river cave in Israel), and a 200 × 140 × 90 m isolated chamber cave (largest chamber cave in Israel). Caves are being discovered at a growing rate, as construction works dig deeper into the subsurface in the crowded city. Some of them are eventually destroyed by the construction works; only presently accessible caves are discussed here. The hydrogeology and hydrochemistry of the Gihon, Jerusalem's main karst spring, was studied in order to understand its behavior, as well as urbanization effects on karst groundwater resources. High-resolution monitoring of the spring discharge, temperature and electrical conductivity, as well as chemical and bacterial analysis demonstrate a rapid response of the spring to rainfall events and human impact. A complex karst system is inferred, including conduit flow, fissure flow and diffuse flow. Electrical conductivity is high compared to nearby springs located at the town margins, indicating considerable urban pollution in the Gihon area. The previously cited pulsating nature of the spring does not exist today. This phenomenon may have ceased due to additional water sources from urban leakage and irrigation feeding the spring. The urbanization of the recharge area thus affects the spring water dramatically, both chemically and hydrologically.

1. Introduction

Famous as a sacred city for the western world religions, it is rarely mentioned that Jerusalem is built on karst. The city was founded just above the Gihon karst spring. This paper briefly presents the karst underlying the city. In addition to the well-developed karst features, human impact on the karst is also discussed. The data comes from ongoing research by Israel Cave Research Center (ICRC) which monitors closely the new caves and karst phenomena found during urban development. The paper deals with presently accessible features, neglecting small isolated chambers and vadose shafts which have been destroyed or filled during construction works.

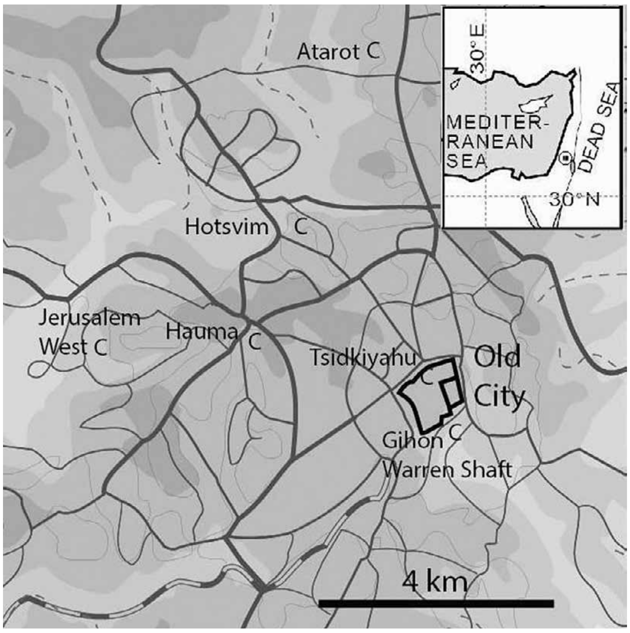

Figure 1. Location topographic map with roads and mentioned caves.

2. Setting

2.1. Topography

Jerusalem is located on hilly surface on both sides of the main water divide of Israel, ~600–800 m above sea level (Fig. 1). The Jerusalem Hills (20 km around Jerusalem) is a structural and topographic saddle within the plateau-like Judean Mountains, at the center of the Judea and Samaria Mountain range. The present topography demonstrates an uplifted Tertiary erosion surface entrenched by fluviokarstic wadies (rarely flowing streams) which drain westward to the Mediterranean and eastward to the Dead Sea. Closed depressions are not observed within the city, but do exist a few km to the north (Frumkin 1993).

2.2. Geology

Jerusalem is underlain by Late Cretaceous rocks. Most of the city is built on Judea Group, dominated by shallow, epiric marine carbonates, on which karst is well-developed (Gill 1997; Picard 1956, Sneh and Avni 2011). The eastern suburbs of the city were recently built on the overlying Mt. Scopus Group, dominated by chalk and some chert deposited in a deeper southern basin of the Neo-Tethys Sea.

The dominant rocks are well-bedded to massive limestones, dolomites and chalk, with smaller amounts of marl and chert. Stratal dip across Jerusalem ranges from 5 to 15° to the southeast, associated with several stages of uplift and folding. Jerusalem was last inundated by marine water probably during the early Eocene. Following regional regression and exposure during the late Eocene, an erosion surface has cut the dipping strata, exposing older layers to the west and younger to the east of the city. Periodic uplift and mild folding was accompanied by continuous karstification and erosion, truncating hundreds of meters of the bedrock (Frumkin 1993).

The section of Judea Group underlying Jerusalem is divided into six sub-units (Sneh and Avni 2011): (A) Cenomanian Kefar Shaul Formation (Dir Yasini, 10–80 m thick) – chalk and well-bedded limestone; (B) Cenomanian-Turonian Weradim Formation (Mizi Yahudi-Ahmar, 55 m thick) – karstified massive to bedded crystalline, dense dolomite; (C) Turonian Shivta Formation (Meleke, 20–40 m thick) – karstified massive, porous biosparitic limestone; (D) Nezer Formation (Mizi Hilu, 40–90 m thick) – well-bedded dense biomicritic limestone; (E) Santonian–Campanian Menuha Formation (60–150 m thick) – biomicritic chalk with some chert; (F) Campanian Mishash Formation (90 m thick) – mainly chalk and chert.

2.3. Climate

Jerusalem is located at the boundary between the temperate Mediterranean climatic belt to the west and the rain-shadow Judean Desert to the east. Mean annual temperature is 18 °C, and precipitation averages 550 $mm.y^{-1}$, falling during the cool winter (October–May), when potential evaporation is ~2 mm/day. The summer (June–September) is hot and dry with potential evaporation ~7 mm/day (Goldriech 1998). During December–January about 2/3 of the annual rainfall occurs, typically concentrated in rainfall events lasting from a few hours to several days. Less commonly, some precipitation falls as snow. August is the hottest month with an average temperature of 24 °C, while the winter average is 10 °C.

About 30% of precipitation flows and infiltrates to the subsurface, and the rest is mostly evapotranspirated. Natural surface runoff amount to few %, but has increased due to urbanization (Benami-Amiel et al. 2010).

Speleothem stable isotopes indicate that glacial periods were wetter and cooler than interglacials (Frumkin et al. 1999; 2000). Increased dust input has contributed to local terra rossa soils, mainly during glacial periods (Frumkin and Stein 2004).

2.4. The urbanization of Jerusalem

During the 2nd millennium Before the Common Era (BCE), Jerusalem occupied ~0.04 km^2 on the hill above the Gihon Spring. The area increased to ~1 km^2 around 700 BCE, and to ~2 km^2 during the Roman period (1st century CE). Following the Arab conquest the city contracted to ~0.85 km^2, within the presently walled Old City (Ben-Aryeh 1977), covering only a small portion of the Gihon Spring catchment. This was followed by rapid growth outside the walls of the Old City, since the mid 19th century. Population has increased from 4,700 in 1525 CE, through 45,000 in 1896, to 933,000 in December 2011.

Today, Jerusalem covers ~130 km^2 (Kaplan et al. 2000). Open area accounts for 65% of the land-use within the municipal area of the city. Land uses in the catchment include small industrial areas, archaeological parks, public administration buildings, religious compounds and mostly residential quarters. The main anthropogenic activities that pose threat to the quality of groundwater are small industry and human residence where sewage infrastructure is old.

Figure 2. Vadose shaft with a trace of meandering canyon at its ceiling. Tsidkiyahu Cave, view upward. Photo by author.

3. Caves in Jerusalem

Few small natural caves were known within the present city borders prior to human intervention. Most known karst caves were truncated by construction works since ancient times. Thousands of years ago, the City of David water systems have truncated some phreatic and vadose voids of local nature. Of these, Warren Shaft is the largest vadose cave, and the Gihon Spring Cave is the largest phreatic cave. Both caves are connected to (but not part of) the famous Siloam Tunnel (Frumkin et al. 2003). In general, most ancient water systems did not follow karst voids (Shimron and Frumkin 2011), but were artificially excavated (Frumkin and Shimron 2006). Underlying the Old City, the large ancient underground quarry dubbed “Tsidkiyahu Cave” (also called “King Solomon Quarry”) truncated some karst voids, mostly vadose shafts (Fig. 2).

Modern construction has truncated many caves, some of which much larger than known before. The longest one is the 800 m long Hauma Cave (Figs. 3, 4), truncated by an artificial shaft 80 m below surface. It is the longest limestone river cave at the northern edge of the Sahara-Arabia desert belt in the Levant, and the 8th longest cave in Israel (Langford and Frumkin 2013). It was explored by the ICRC upstream until becoming a narrow tube-like conduit, and downstream down to a sump.

Figure 3. Vadose canyon in Hauma Cave. Photo by author.

The cave is mostly a low-gradient dip passage perched on Kefar Shaul Formation, with a ten m vertical segment. The cave is mostly a vadose canyon with remnants of an original phreatic tube. Some 16 vadose shafts are connected to the stream passage, forming "domepits" up to 32 m above stream level.

The largest volume chamber under Jerusalem (and in Israel) is Atarot Cave, at Atarot industrial zone (Fig. 5). It is a 200 × 140 m large isolated chamber cave (Frumkin and Fischhendler 2005), with 90 m maximal depth. It was formed in Shivta Formation probably under phreatic (hypogenic?) conditions, but large scale collapse features conceal the original solutional morphology. The chamber intersects some vadose shafts. The Atarot Cave is well-decorated with speleothems (Fig. 6), but unfortunately, it was partly rubble-filled by construction contractors before it was known to speleologists and authorities.

Hotsvim Cave (Fig. 7) is another chamber cave, truncated by a building at Har-Hotsvim industrial zone. This cave is a symbol of cave conservation in Jerusalem, as the building plan above it was altered in order to preserve the cave.

Among the vadose shafts truncated by construction works, the Jerusalem-West Cave is one of the most studied in the city. This small shaft system in the western suburb of Har-Nof was blasted by a contractor; consequently its speleothems were used for paleoclimatic reconstruction of the last 220,000 years (Frumkin et al. 1999; 2000). This exceptional, almost continuous record has shown that regional climate was much wetter and dustier during glacial periods (Frumkin and Stein 2004).

Relict karst features in Jerusalem include a wide range of dissolution voids filled with breccias of chert fragments, derived from collapse, erosion and disintegration of Menuha and Mishash Formations chert layers. Some of these voids reach deep into the Judea Group rocks. These voids are probably associated with deep karstification of the Tertiary Judean erosion surface. An age of at least early Pleistocene is indicated by archaeozoologic deposit in one such pit at nearby Bethlehem (Hooijer 1958). Their geology has been properly described following their discovery (Picard 1956; Shaw 1961), but unfortunately, they were misinterpreted in later publications (e.g., Horowitz 1970; Sass and Freund 1977).

4. Gihon Spring hydrology

Gihon is the largest karst spring in Jerusalem (Fig. 7), and the reason for its original location. Gihon recharge zone is within the older parts of Jerusalem, on Judea Group outcrops (Cenomanian–Turonian carbonates). The Spring emerges 635 m asl within a small phreatic cave, 3 m below the current Qidron Valley level, whose lower channel is filled with thick debris. The spring hydrology was studied by Benami-Amiel et al. (2010).

We cleared out the Gihon Spring cave from debris. It was found that the water emerges into the cave from an underwater (~130 cm below water surface) vertical fissure ~1.5 cm wide in Mizi Ahmar dolomite (Gill, 1997).

Discharge, temperature and electric conductivity (EC) were measured continuously during 2004/5. Discharge during the

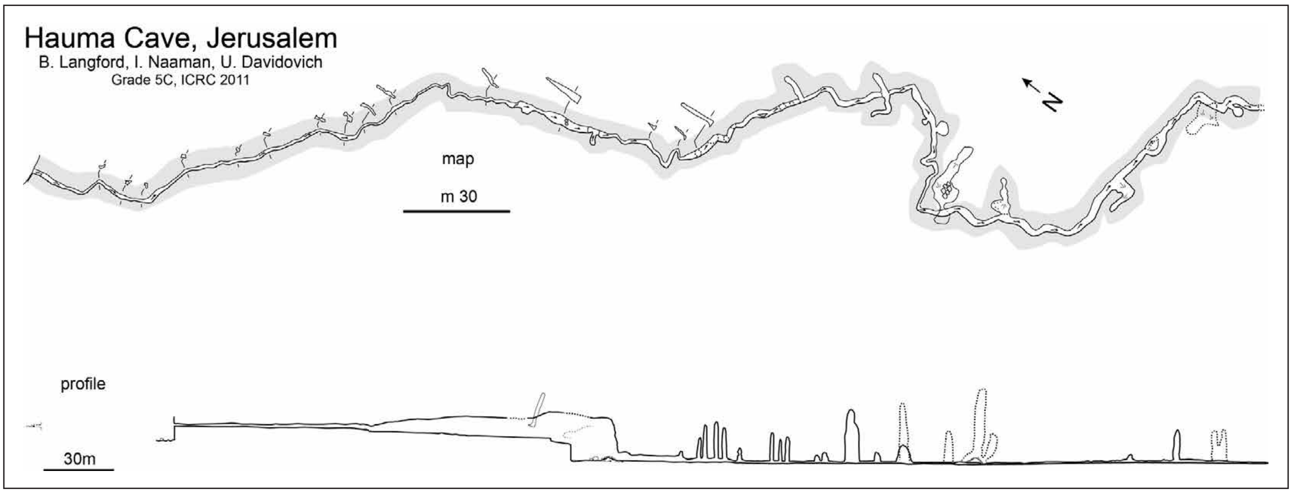

Figure 4. Hauma Cave – vadose river cave, survey by Boaz Langford.

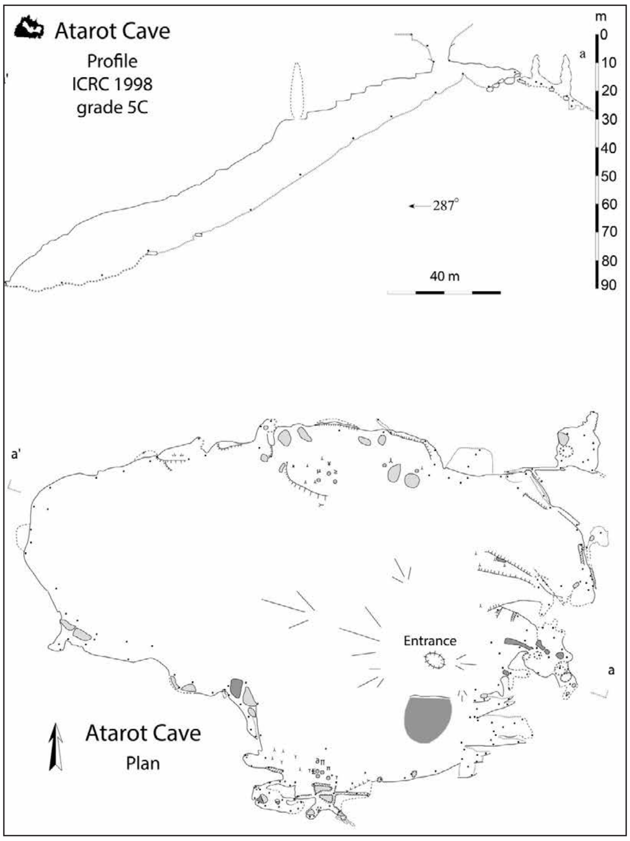

Figure 5. Atarot Cave survey – the largest chamber cave in Israel. In gray areas the fill reaches the ceiling.

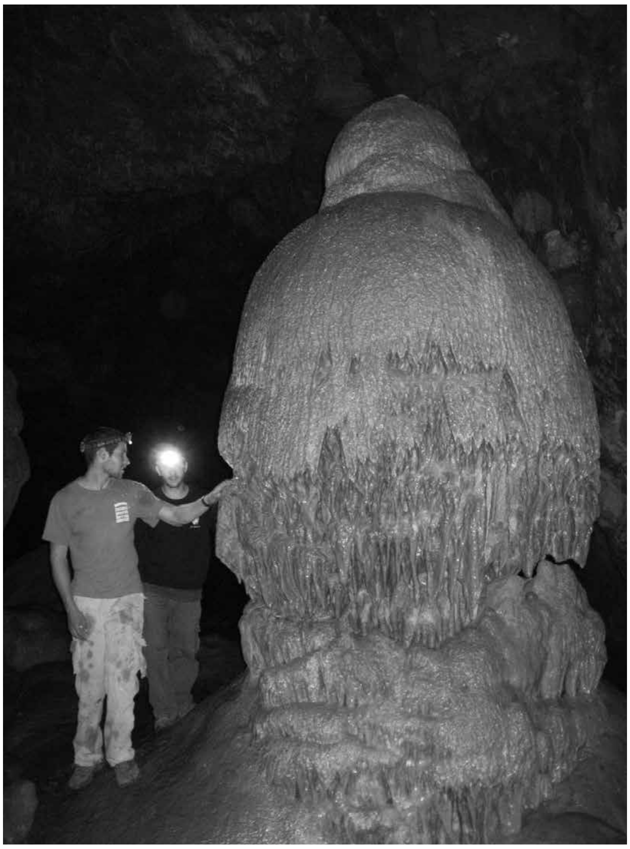

Figure 6. A stalagmite in Atarot Cave.

dry summer is relatively stable, ~0.01–0.03 $m^3.s^{-1}$. During the investigated hydrological year (2004/5; 564 mm precipitation) spring discharge started at 0.025 $m^3.s^{-1}$ (October), peaked at 0.164 $m^3.s^{-1}$ (February), and recovered by the end of the year (September) to 0.031 $m^3.s^{-1}$. During rainstorms and soon afterwards, quick-flow response time ranged from 3.5 to 89 hours, depending on rainstorm type, rainfall amount, and the previous saturation of the system with water. A century ago Vincent (1911) observed discharge pulses ("ebb and flow") in the Gihon Spring:

"… water emerges accompanied by loud echoing noise heard 1–2 min before the water rises and during the whole period of the strongest flow… water rushed out unexpectedly every two or three hours, running for twelve or fifteen minutes at a time."

Today the Gihon Spring is not pulsating any more, possibly due to anthropogenic impact. We suggest that water sources added to the recharge (from irrigation and pipe losses) within the city may continuously fill the underground "siphon" feeding the spring. External water import to Jerusalem has increased substantially overtime with the development and expansion of the city.

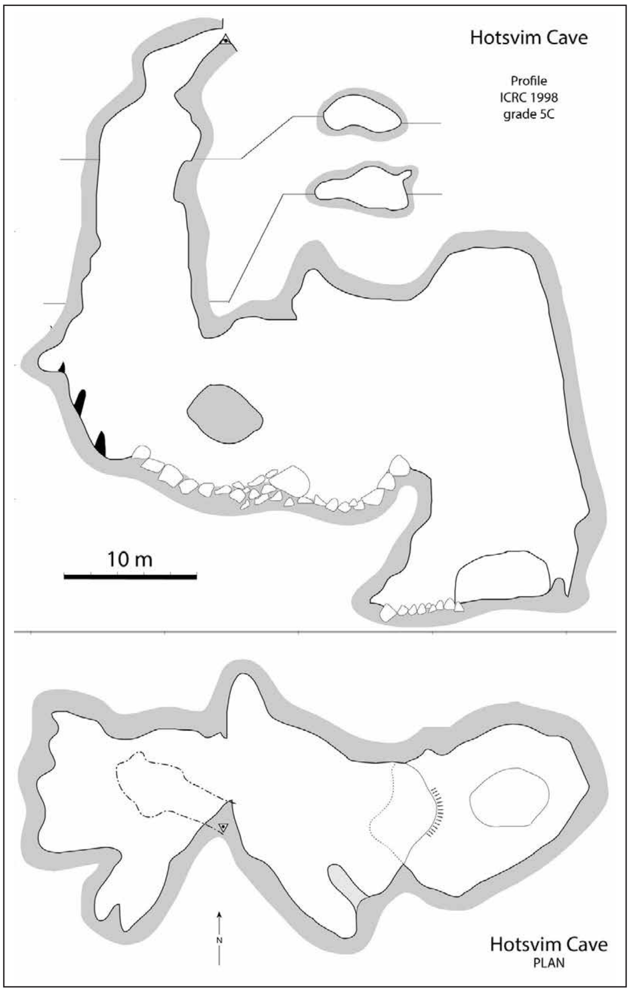

Figure 7. Hotsvim Cave survey.

The average EC is relatively high (1.54 $mS.cm^{-1}$) compared with other springs around Jerusalem, especially those in nearby natural open areas (~0.6 $mS.cm^{-1}$). The EC fluctuates considerately: Maximal EC (2.39 $mS.cm^{-1}$) was recorded at the end of the dry season and minimal EC (1.278 $mS.cm^{-1}$) on February at the peak of the rainy season. Temperature of the water is more stable – between 19.03 °C during wintertime (February) up to 19.42 °C at the end of the dry season (September).

Water temperature and EC minima are closely associated with rainfall peaks. The EC and temperature values began to decline 9–18 hours after rainfall began, and reached minimum values 8–48 hours later. After about 8 days, both values recovered to their initial values.

Despite large air temperature variations, water temperature fluctuates only slightly, indicating the dominance of rock temperature on fissure water. Water temperature is higher than average air temperature, explained by the geothermal gradient of the Judea Group stratum and the water residence time in the host rock.

The Gihon Spring rather small temperature fluctuations correlate with the EC. As expected, arrival of fresh rainwater results in lower solute concentration, EC and temperature.

The saturation index (SI) of the water indicates that the water is always under-saturated with respect to dolomite (and evaporites). Super-saturation with respect to calcite was recorded in some samples, suggesting possible calcite precipitation. Historic calcite tufa deposits of the Gihon waters (Frumkin and Shimron 2006) indicate that super-saturation with respect to calcite is a recurring phenomenon. These results match the characteristics of the aquifer: the quick flow component of the water is often under-saturated, although baseflow waters can become super-saturated with respect to calcite, especially under free-flow conditions in the Siloam Tunnel downstream of the spring, where rapid CO_2 degassing occurs.

Figure 8. The study of Gihon Spring.

Due to the quick flow component of karst springs they are vulnerable to rapid pollution. Indeed, a major pollution event occurred on May 2002. This event occurred due to leakage from a sewage pipeline about 1.2 km north of the spring.

5. Conclusions

Although the topography of Jerusalem seems fluvial, its karstic nature is revealed by underground features and, to a minor extent, by subaerial morphology. The underground karst voids incloude a river cave, vadose shafts (Fig. 9) and ancient isolated chambers. The discussed caves were found due to truncation by anthropogenic construction works. The Gihon karst spring reflects typical karst hydrology with increasing human interference by pollution and modification of the flow regime. Modern infrastructure is increasingly moving to the subsurface; karst features are intercepted at an accelerated rate and should be closely monitored and preserved wherever possible; the ICRC is doing its best in both these respets.

Figure 9. Vadose shaft truncated by construction works. Close and similar to Jerusalem West Cave. Photo by author.

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