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Nabataean Water Supply Systems: Appropriateness, Design, and Evolution

A full understanding of Nabataean society, economy, and settlement strategies depends, in large part, on a thorough knowledge of the way in which the Nabataeans dealt with the problems of water supply and agriculture throughout their largely desert kingdom (Oleson 2001a). In much of the northern Nabataean territory or at higher altitudes, for example near Wādī Mūsā or around 'Ammān, annual direct precipitation was sufficient to allow drought farming without extensive human intervention. But elsewhere, as around ancient Ḥawrā' (modern Al-Ḥumayma) in Jordan's southern desert, all crops required irrigation through the harvesting of run-off water from occasional rain showers. The provision of drinking water for humans and their domestic animals relied everywhere on some combination of cisterns, wells, springs, and aqueducts, but the character of each system varied according to local circumstances of topography and water sources, and techniques naturally evolved over time. Nabataean hydraulic techniques were based in part on regimes inherited from their Bronze Age and Iron Age predecessors, and on some Hellenistic Greek accomplishments, such as the reservoirs roofed with stone slabs carried on transverse arches, found on Delos and other arid Aegean islands. Nevertheless, the final systems bear an unmistakable local stamp.[1] Both large settlements, such as Petra, and small ones, like Ḥawrā', depended on water-supply and agricultural systems that were the result of numerous interrelated decisions. The final arrangements were determined not only by local topography, geology, and hydrology, but also by size of the population, character of the economic system, choice of crops and domestic animals, and political and cultural forces. This paper will present a brief account and analysis of the desert water-manipulation regimes at Ḥawrā' documented for the Nabataeans before and after the Roman conquest. Case studies of individual sites, such as those for Ḥawrā' and Petra, are the best route to a full understanding of the relationship between hydraulic technology and Nabataean society.

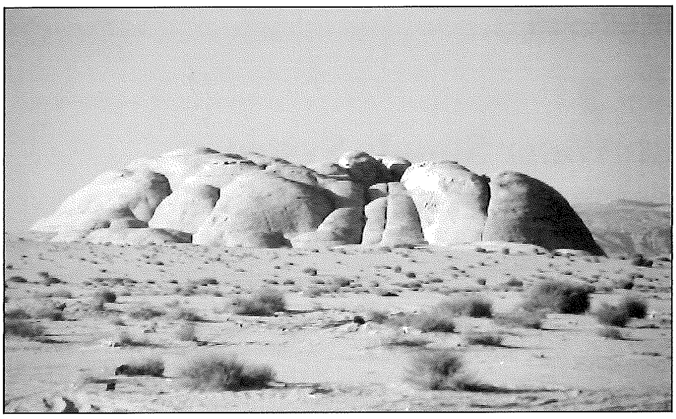
The Nabataean settlement centre of Ḥawrā' was founded sometime in the first century BC at a previously unoccupied site. An account of the foundation, part of the first book of Uranius's *Arabica,* names a King Aretas as the founder.

Auara: a town in Arabia, named by Aretas from an oracular response given to his father Obodas. Aretas set out in search of the oracle's meaning, for the oracle said "to seek out a place *auara*" — which in the Arabian and Syrian languages means "white" And as he lay in wait, a vision appeared to him of a man clothed in white garments riding along on a white dromedary. But when the apparition vanished, a craggy hill appeared, quite natural and rooted in the earth; and there he founded the town.

The punning value of the Nabataean name and the totemic animal probably have something to do with the hump-like ridges of white Disi sandstone that are such a prominent part of the landscape around al-Ḥumayma (FIG. 1).

Unfortunately, the text does not explicitly indicate whether King Aretas III (85-62/61 or 60/58 BC) is intended, or Aretas IV (9/8 BC-AD 39/40), and the artifacts from the earliest occupation levels at the site cannot be dated with sufficient accuracy

[1] For the Hellenistic influence, see Oleson 1991, 1992a, 1992b. On Nabataean water-supply systems in general, see Oleson 1995, 2001a, Bellwald and al-Huneidi 2003.



1. Hump-shaped jabal northeast of al-Ḥumayma.

to support either interpretation.[2] The context of intentional sedentarization at Ḥawrā' fits in particularly well, however, with the mid-first century BC. At this time King Aretas III fostered sedentarization, Hellenization, and an enhanced monarchy in order to stay competitive in long distance trade, to fill the power gap left by the Seleucids in Syria, and to compete with the Ptolemies of Egypt (Schmid 2001a: 415, 2001b: 370-71; cf. Parr 1978; Young 2001: 100-12). Aretas III's royal epithet, "Philhellene", emphasizes his connections with the Hellenistic world, and in the second quarter of the first century BC Petra was transformed by settlement, stone houses and an aqueduct, and the organization of long-distance trade (Schmid 2000: 123-27; Bellwald and al-Huneidi 2003: 4, 35). The Romans also recognized the importance of Ḥawrā', constructing a fort there immediately after the conquest of the kingdom in 106 (Oleson 2001b, 2003), as did the Abbasids, who purchased it in the late seventh century (Foote 1999; Schick 1995: 312-13).

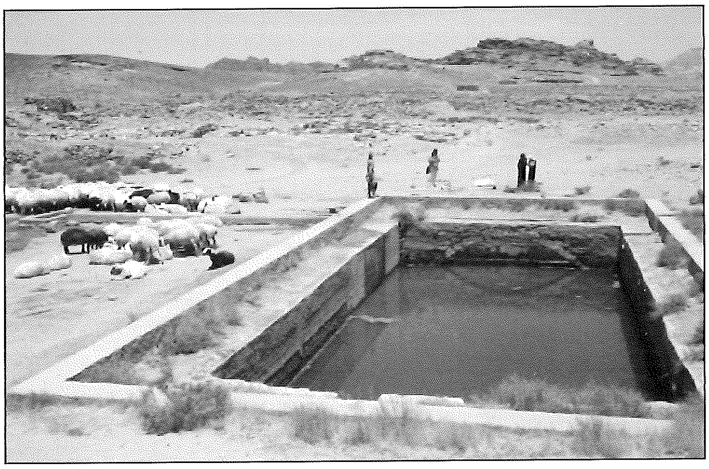
The foundation story is a historical *topos*, involving a king, an oracle, a successful vision quest, and a topographical landmark, but let us assume for the moment that it reflects reality and try to recreate the event. When Aretas III stood blinking in the desert sun after his vision had evaporated, some characteristics of the landscape must have convinced him that the divine guidance was based on an appreciation of practical human needs, particularly the potential water-supply. As Aretas looked around with the keen eyes of a desert dweller, the advantages of the site were obvious. Regional patterns of precipitation undoubtedly were common knowledge among the Nabataeans, but a glance at the local vegetation also provided Aretas with information on the extent and reliability of the rainfall in this particular locality. At Ḥawrā', annual precipitation totals about 80mm, very low, but predictable. Aretas could also see the ash-Sharā Escarpment towering above the desert to the north, an obstacle that caught winter rainstorms and channeled enormous amounts of run-off water into the Wādī Qalkha, which skirted the eastern boundary of the future settlement. The white sandstone ridges to the east and southeast formed enormous catchments that shed run-off water on large areas of relatively fertile and easily cultivated soil in close proximity to the site. Aretas also noted that an eroded Pleistocene lake bed at the northwest edge of the settlement site constituted a large catchment field focused on the location indicated by the vision, but at a slope allowing relatively easy control of the water. Experience at Petra had already shown that the red and white sandstones around Ḥawrā' were sufficiently impermeable to allow the excavation of cisterns (Bellwald and al-Huneidi 2003: 17-21). Finally, this ambitious king must have found the green smudges surrounding the far-off springs high on the escarpment a tantalizing promise of spring water. The resources at this previously uninhabited spot were more than sufficient to support pastoral and agricultural activities, and the location, on an established caravan route, was well placed to satisfy the political and economic needs of a society newly energized by the absorption of Hellenistic culture and involvement in transit trade between

[2] Preserved in Stephanus of Byzantium, 144, 19-26; cf. Jacoby 1958: Preserved in Stephanus of Byzantium, 144, 19-26; cf. Jacoby 1958: 340. Although the Nabataean king list is not certain until Obodas III (30-9BC), most recent reconstructions indicate that the reigns of both Aretas III (85-62/61 or 60/59BC) and Aretas IV (9/8BC-39/40AD) followed those of kings named Obodas (Obodas I, 96-85BC and Obodas III) (Fiema and Jones 1990). Aretas IV, however, was not in fact the son of Obodas III (Josephus, *Ant* 16.9.4; Starkey 1965: 907-9, 913-14; Wenning 1993: 34), so if we interpret strictly the terms "son" and "father" used in the passage from Uranius, Aretas III should be the founder of al-Ḥumayma. Recently, there has been a proposal to move the reign of Rabbel I from the mid-second century down to 85/84BC, placing him between Obodas I and Aretas III (Wenning 1993: 30-31; Schmid in Frösén and Fiema 2002: 254). But since the reconstructed reign is only one year, this interpolation does not invalidate the dynastic link between Obodas I and Aretas III. Furthermore, Wenning assumes that Rabbel I and Aretas III were brothers, both sons of Obodas I. On the foundation of Ḥawrā', see now also (Hackl, Jenni, Schneider 2003: 280-82, 294, 596), who propose several unsustainable hypotheses about the name of the site.
A worn coin possibly struck by Aretas III was found in a surface layer at the site (reg. no. 1998.0484.01), but it may or may not have been brought to the site during his reign. For an account of recent excavations at the site, see (Oleson *et al.* 1999, 2003).

Southern Arabia and the Mediterranean.[3] This site called "White" had great promise.

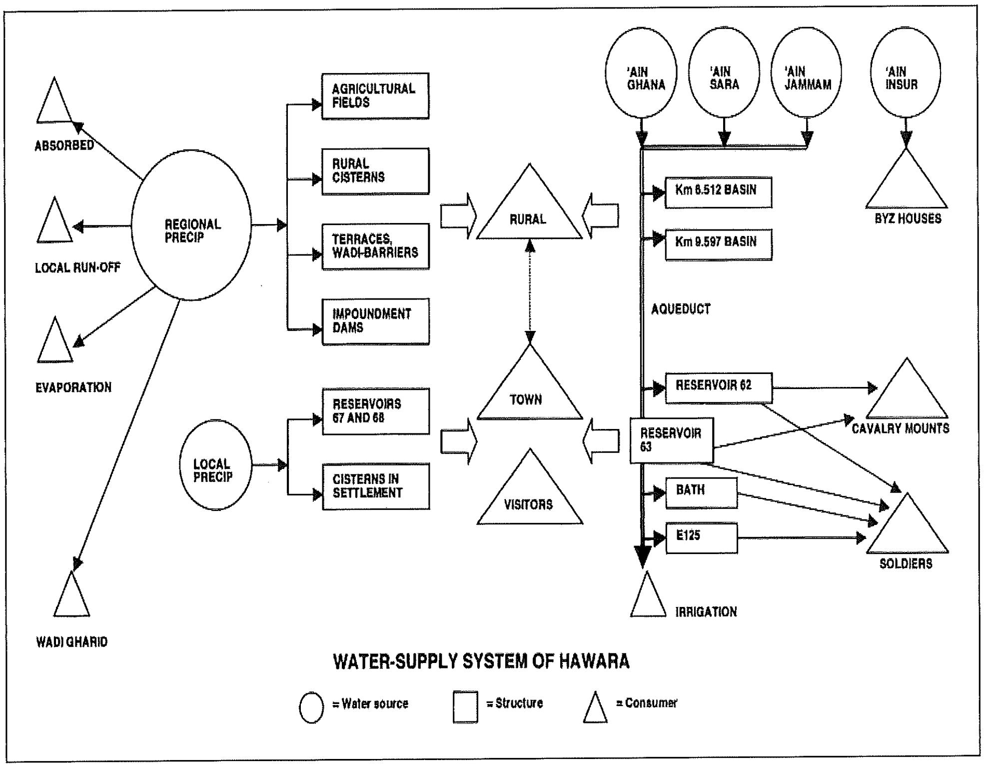
Back to reality, the water-supply system of Ḥawrā' involved input from precipitation and springs, artificial structures for transporting and storing the water, enhanced soil storage, direct consumers, and natural losses. A diagram of the system as it functioned from the arrival of the Roman garrison to the abandonment of the fort around 400AD clarifies the input and consumption patterns (FIG. 2). In fact, the only Roman period and later modifications to the Nabataean system were the addition of more consumers and the diversion of some of the aqueduct flow to the fort reservoir and a Roman bath.

The main lines of the chronology and evolution of the water-supply system serving Nabataean Ḥawrā' and the succeeding ancient communities are clear. Permanent occupation of the site would have been impossible without facilities for storing run-off water, and a pair of reservoirs in the settlement centre belongs to the foundation period (FIG. 3). Given their atypical size and design, it is likely that these reservoirs were commissioned by the royal founder. Soon after, private individuals attracted to the site by the public water system, and presumably by promises of arable land, began



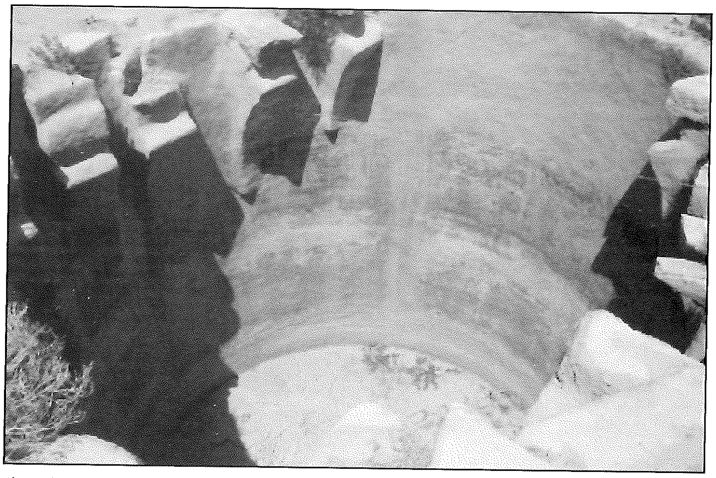
3. Reservoir in settlement centre (survey nos. 67), view.

to build or excavate cisterns to collect run-off water in the settlement centre, the surrounding hillsides, and throughout the catchment region, to supplement the public supply. Seven cylindrical cisterns were built along the path the run-off followed through the settlement centre; they may have been used for some time by tent-dwellers before houses were constructed around them (FIG. 4). The aqueduct, and the pool it filled at the north edge of the settlement, belong to the end of the first century BC or very beginning of the first century AD (FIG. 5). Given the design of the pool, the whole aqueduct system now seems, surprisingly, in large part

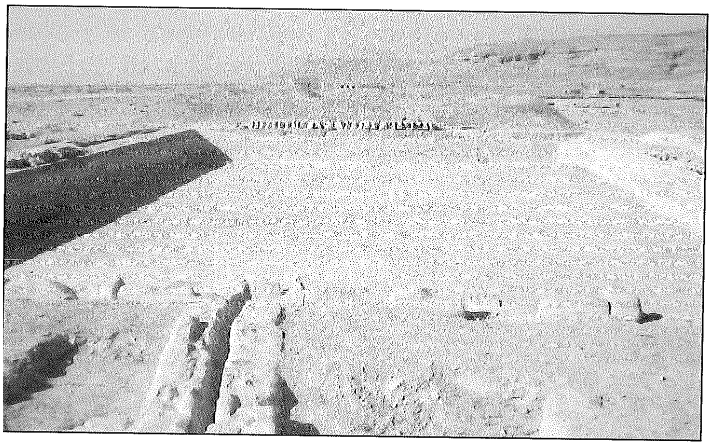


2. Diagram of Ḥawrā' water-supply system.

[3] The old King's Highway (*Numbers* 20:17, 21:22) must have passed across or close to the site, since its reincarnation as the *Via Nova Traiana* passed through Ḥawrā' (Graf 1995: 256-57; Bienkowski 2001: 348; Freeman 2001: 433; Young 2001: 97-99).



4. Cylindrical domestic cistern in settlement centre (survey no. 54), view.



5. Aqueduct pool in settlement centre (survey no. 63), view.

a prestige project built by King Aretas IV on the model of his pool and garden complex at Petra, designed to highlight, in a spectacular manner, Nabataean control of the desert (Bedal 2001). If Ḥawrā' was in fact founded by Aretas IV rather than Aretas III, the aqueduct and three reservoirs in the settlement centre represent part of a very ambitious and comprehensive regional water-supply system. The aqueduct discharge caught by the pool was most likely used for livestock, craft processes, agricultural irrigation, and bathing. There may have been a Nabataean bath house as well, 100m south of the aqueduct reservoir (Reeves and Oleson 1997).

In the reign of Trajan, or soon after following the conquest of the Nabataean kingdom, the Romans constructed a fort, including a reservoir fed by a branch line from the aqueduct. At least some of the overflow from the reservoir served a pressurized water system in the fort. Later on, in the second or early in the third century, the free-flowing overflow conduit at the aqueduct pool was replaced by a stopcock and pressurized pipe providing water to a heated bath constructed over the remains of the Nabataean structure to the south (Oleson 1988, 1990). The stopcock is a metaphor for the more formal Roman methods of administering water supplies. All or some of the remaining aqueduct discharge was diverted through terracotta pipelines to the *vicus* associated with the fort.

Very few of the other elements of the water-supply system in the settlement centre and throughout the catchment can be dated with any precision on the basis of artifacts, particularly the many cisterns. Nevertheless, the design and execution of most of the structures, and the associated sherd scatters or occasional block-like representations of the god *Dhūsharā*, are Nabataean in character and indicate that the regional system was for the most part complete by the second century AD. Furthermore, no cisterns were built into Ḥawrā's five known Byzantine churches, as at Petra, Mampsis, Oboda, and other sites in the region (Fiema *et al.* 2001: 70-73; Negev 1988: 36-38, 57; Negev 1997: 109-13, 129; Shereshevski 1991), indicating that the reservoirs and cisterns in the settlement centre already provided sufficient capacity. The Roman foot (*pes monetalis*, 0.296m) does not appear in use outside the Roman fort, and the Byzantine foot of 0.3089m, which was used for the Ḥawrā' churches, does not appear as the planning module for any of the cisterns or reservoirs in the settlement centre or surrounding region. There is also no indication that cisterns were constructed in the early Islamic period. None have been found in the Abbasid family manor house. Renovation of older storage structures, of course, was ongoing, and many of them are still in use today. This regional, largely Nabataean, system includes 27km of aqueduct, five reservoirs, 57 cisterns, three containment dams, along with numerous wadi barriers, and a few terraced fields.

How did this water-supply system relate to settlement patterns? The applications to which water might be put in a small, pre-modern settlement in the Jordan desert are varied, but predictable. The highest priority use, of course, was direct human consumption. An average adult accustomed to an active life in this arid environment needs to consume approximately 2.0 litres of water per day in order to feel comfortable. In addition, water is required for cooking, and for washing the body, clothing, and eating utensils. Estimates of the amount of water needed in antiquity to satisfy all these basic human needs (including drinking) vary, but 8.0 l per day is a reasonable minimum figure (Helms 1981: 188-89, 1982; Evenari, Shanan and Tadmor 1982: 148; de Vries 1987). If we assume that all the water in the reservoirs and cisterns in the habitation centre was intended entirely for human consumption, and that the system was designed with a safety margin of 100% — that is, the inhabitants counted on the cisterns being filled only every second year (cf. Shereshevski 1991: 191-93) — the 2300m^3 stored there could have sustained a population of approximately 390 souls. This figure excludes the aqueduct discharge and its pool, which may have been used for other purposes, and the Roman reservoir no. 62, which is part of an essentially separate and later system.

The eleven domestic cisterns found in the settlement centre can serve as a check. They have an average capacity of 122.25m^3, a total capacity of 1,345m^3. Assuming the 100% safety margin, an average capacity domestic cistern could support 21 individuals, and all eleven together 230 individuals. Given the significant size of the domestic structures visible at present in the settlement centre, an estimate of 21 individuals per household does not seem excessive — assuming the presence of several generations of the family, closely associated clan members, servants or slaves, and visitors.

The reservoir in the Roman fort was undoubtedly refreshed at frequent intervals from the aqueduct, but any calculation of the through-flow remains completely conjectural. Although the dimensions of this reservoir — 10 x 50 x 100 Roman feet — are too regular to suggest that the resulting volume (1,273m^3) had been carefully calculated to support a certain anticipated garrison size, the planners must have considered the possibility of withstanding a siege after interdiction of the aqueduct flow. Assuming loss of half the water in the unroofed reservoir to evaporation, which can total 3.4m/year in this region (Natural Resources Authority 1977: Map SW-5), and a hypothetical worst-case siege lasting no longer than six months, the water stored in the reservoir could have supported a human garrison numbering approximately 436. This figure corresponds well enough with the size of the camp, which is suitable for an auxiliary *cohort* of approximately 500 men (Parker 1986: 105; Webster 1985: 145-51). Any mounts present in the fort, of course, would have required a large daily allowance of water as well.

The maximum possible flow of the aqueduct can be calculated as 19.6m^3/hour. Any discharge from the aqueduct could have supplemented the stored water. If we assume a real, average discharge of half the theoretical maximum, or 9.8m^3/hour, and diversion of 63.7m^3/day to the fort reservoir (an amount which would have replaced the stored water every 20 days), the hypothetical resulting daily discharge of 171.5m^3 still could have sustained an astonishing 21,000 individuals. The daily discharge, or course, may have been much less, and in fact it is likely that very little of the aqueduct water was used for human consumption, since the pool it feeds is better suited for swimming or irrigation than for the storage or provision of drinking water for humans.

Some of the water available in and near the settlement centre and much of the water in the rural cisterns must have been designated for use by livestock. If we assume that half of the capacity of the two central, public reservoirs was designated for consumption by animals, the potential population supported by water stored in the civilian centre falls to 310. As for the livestock, camels and donkeys require approximately 5.0 litres/day when eating dry fodder, goats or sheep 3.0 l/day (Helms 1981: 188-89, 1982: 97-113; Evenari, Shanan and Tadmor 1982: 148; de Vries 1987). If we assume that the herds consisted of 10 percent camels and donkeys, along with 90 percent goats and sheep, we get the figures of approximately 18 camels or donkeys and 183 ovicaprids supported by a 50 percent share of the water in the two public cisterns. It is reasonable to assume that 90 percent of the 7,994m^3 of water stored in the reservoir, cisterns, off-take tanks, and dammed pools outside the settlement centre was intended for livestock, since the human population was more thinly scattered in the rural district, and since unroofed pools holding poor-quality water constitute 44 percent of the total. Assuming both a safety margin of 100 percent, and the same proportion of camels, sheep and goats as in the settlement centre, this water supply could have supported 140 persons, 280 camels or donkeys, and 2,800 ovicaprids. The combined regional total is 450 persons, 300 camels or donkeys, and 3,000 ovicaprids. This figure, of course, is a minimum, since the output of the aqueduct is ignored and 100 percent redundancy is assumed.

The resulting regional population density reconstructed from these calculations is 2.2 persons/km^2. These figures, of course, are highly hypothetical, but they give an idea of the significant carrying capacity of this arid landscape. In the 1977 National Water Master Plan of Jordan, al-Ḥumayma is counted as part of the Wādī ar-Rummān Catchment, an area of 1416km^2. The population of this region in 1975 was 3,918, or 3.0 inhabitants/km^2 (National Resources Authority 1977: Map ED11). Since there have been improvements in nutrition, health care, and security and a subsequent rise in population in the later twentieth century, the hypothetical density of 2.2 persons/km^2 for the catchment area of ancient Ḥawrā' seems reasonable.

Although the total maximum amount of stored water in the Ḥawrā' water-supply system is impressive (12,345m^3), it constitutes only a tiny fraction of the total amount of run-off theoretically available in the catchment area (between 320,000 and 2.4 million m^3). In fact, in antiquity as today the activity "consuming" the largest amount of water in the catchment was agriculture. There were numerous fields in and around the wadi beds and at the foot of natural run-off catchments that effectively multiplied the available precipitation. These were provided with low earth or stone barriers to slow the passing streams and allow the water to soak into the soil. The fields that received sufficient moisture during the winter rains were seeded with wheat or barley and protected from grazing until the crop had been harvested. Both six-rowed barley (*Hordeum vulgare*) and bread wheat (*Triticum aestivum*) are extensively represented in the plant remains from al-Ḥumayma (Oleson 1997). It is impossible to reconstruct how much water was "consumed" in this fashion around Ḥawrā', but it must have been many times the volume of the stored drinking water. In the Negev, the minimum annual amount of precipitation needed to grow barley without irrigation is around 230mm, a consumption of approximately 2,300m^3/ha; for wheat the figure is 250mm or 2,500m^3/ha (Evenari, Shanan and Tadmor 1982: 191-205; Hillel 1982: 148). If all the water stored artificially in the al-Ḥumayma catchment were used for irrigating this type of crop, it would have sufficed for only about 5.0ha of fields, sufficient to sustain only eight persons. Although production of grain by direct, artificial irrigation would have been impossible, archaeological and literary evidence testify to the irrigation of small patches of vegetables, grapes, and fruit and olive trees in the immediate vicinity of Ḥawrā' (Oleson 1997), both from cisterns and by making use of the aqueduct run-off. At least one rock-cut wine press can be seen near al-Ḥumayma (Oleson survey no. 51), indicating the presence of a vineyard that would have required irrigation. The 500 olive trees planted by 'Ali ibn 'Abd Allāh ibn al-'Abbas required some irrigation as well (al-Duri and al-Mutallabi 1971: 107, 108, 149, 154; al-Balādhurī 1978: iii, 75). Olive, fig, and apple trees have been cultivated with modest success by landowners at the site over the past 50 years.

Could the run-off water provided by the al-Ḥumayma catchment have supported sufficient agricultural activity to sustain the hypothetical minimum population of 450 persons? Assuming that the farmers of Ḥawrā' experienced an average yield 646kg of wheat per hectare — as restored for the ancient farmers of the Negev (Bruins 1986: 86-95) — that they kept back one-third as seed (215kg), and that 10 percent of the remaining grain was lost (43kg), each hectare would have produced 388kg of wheat for consumption. Since a human needs approximately 250kg of wheat per year to survive (Broshi 1980; Bruins 1986: 175-81), 288ha of wheat fields would have been required to feed the hypothetical minimum population in the Ḥawrā' catchment. A well-documented "principle of least effort" tends to restrict field agriculture to within a radius of 5km of a traditional Middle Eastern settlement (Simmons 1981; Beaumont *et al.* 1976: 164-65; Wagstaff 1985: 52-53). Tree crops can be cultivated at a greater distance, while critical hunting and gathering activities can take place up to 10km or a two-hour walk away from the settlement. The plots recently tilled by the Bedouin are in fact generally within a 5km radius of al-Ḥumayma. Since even one-quarter of the territory within a circle 5km in diameter equals 2,000ha, it is clear that just the fields in the immediate vicinity of Ḥawrā' could have provided sufficient grain to support a regional population much larger than 450 persons.

In summary, the occupants of Ḥawrā' created a water-supply strategy appropriate to local conditions and materials and dependent on technologies developed or perfected over the previous century at other Nabataean settlement sites. The system was linked with a mixed pastoral/agricultural economic strategy enlivened by the presence of a long-distance trade route, and it allowed a density of occupation close to that supported in recent times by a more complex and integrated economy. The system functioned well enough that there was little expansion of the original facilities after the fall of the Nabataean kingdom, despite continued intense occupation of the site through the Early Islamic period. There are still some issues associated with Nabataean water-supply that we know little about: for example, planning procedures; sources of funding; the composition and organization of teams of designers and builders; construction procedures; the local administration and division of water; ownership water rights; responses to variation in run-off or spring flow; religious beliefs and rituals surrounding consumption and actual consumption rates for humans, large and small livestock, and crops. Nevertheless, it is clear that King Aretas planned a sustainable water-supply system that functioned effectively in a hyper-arid desert for 800 years.

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