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The Udhruh region: A green desert in the hinterland of ancient Petra

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Abstract

This chapter presents the preliminary results of an ongoing fieldwork project in the region of Udhruh (southern Jordan). It focuses on and discusses the ancient agro-hydrological activities and practices of the study area. First it gives an introduction about the history of settlements (with historical and archaeological evidence), and about the environmental and geoarchaeological settings. The second part of the chapter discusses the archaeological results pertaining to the ancient water-harvesting systems, together with the related agriculture fields, and the integrated technical and interdisciplinary approaches required to study them further.

> In the thirty-second year of the reign of … Flavius Justinianus, … three days before the Kalends of January, in the four hundred and [fifty]-third year of the province …. To the most respectable Flavius Valens, son of Auxolaos, tax collector of the current seventh indiction and through you to the present and future tax collectors of this city of the Petraeans … I sold to the most God-pleasing Philoumenos, son of Geriontos, … [one] well-watered field that belongs to me [in] the hamlet [ ]aina, near Augustopolis, called Mal-el-Amoa[?] or Mal-[al]-Etherro[ ]eïba, with every right, and I surrendered corporeally its possession. … (I,) the above-written Theodoros, son of Obodianos, have requested that … my person and property and account be relieved of the tax contribution assigned to me for the above-written well-watered field. … from the total landholdings of

Augustopolis each [year, with a plot size of] one (and) one ninth *iugerum* of the (imperial) *patrimonium*.

Petra Papyrus 25, 30 January AD 559.

Introduction

Access to fresh water is one of the greatest global challenges of the twenty-first century. Scholars from different fields of research around the world are dealing with the ever-growing demand for, and the severe supply constraints upon, water. Rapid population growth and changing climatological conditions, especially in some of the most water-scarce regions of the world, result in increasing pressures on already overexploited water resources. This is especially the case in the arid and semi-arid parts of the Middle East, North and sub-Saharan Africa, where almost all the water is used for agricultural purposes (see Gleick, 2014: 227–35, Table 2). Not only is the annual precipitation in such regions low and poorly distributed over the crop-growing seasons, but a large part of it gets lost before it becomes available for agricultural use. In semi-arid regions of sub-Saharan Africa, between 30 and 50 per cent of the precipitation evaporates from the soil surface and after shallow infiltration, and can be considered non-productive water loss (Rockström and Falkenmark, 2000: 335, and references therein). A productive transpiration flow of 15 to 30 per cent of the precipitation re-enters the atmosphere via the stomata in the leaves of the vegetation coverage, while 10 to 25 per cent runs off and 10 to 30 per cent replenishes the groundwater through deep percolation. Different methods and techniques of water harvesting are employed to increase the availability of fresh water to agricultural crops in arid and semi-arid regions (Oweis et al., 2012: 3–71).

It is clear from archaeological research that ancient societies were dealing with similar problems. This chapter will shed some insights into how people practised water procurement for agricultural purposes in the hinterland of Petra (Jordan) in antiquity. After several years of archaeological fieldwork, the authors can already state that the research area around the village of Udhruh is one of the most complete and best-preserved field 'laboratories' available for studying the long-term development of innovative water-management and agricultural systems in southern Jordan, between the first century BC and the tenth century AD (Nabataean, Roman, Byzantine and early Islamic periods). Although the Udhruh Archaeological Project is still ongoing, we would already like to present some preliminary results about the ancient agro-hydrological systems.

The antique settlement of Udhruh and its environs

Background and research

The village of Udhruh, east of Petra, was an almost forgotten archaeological site until Fawzi Abudanah drew attention back to it with his large-scale surveys (Abudanh, 2006). Earlier explorations and excavations revealed that Udhruh had housed an important Nabataean settlement and a Roman legionary fortress.[1] The current village of Udhruh is dominated by and centred on the still-standing remains of this fort, which was transformed into a town in post-Roman times. Classical literary and archaeological sources point to a long-term development from Nabataean to Islamic times (Fiema, 2002; Kennedy and Falahat, 2008). The archaeological variety and perfect preservation of the area surrounding Udhruh were, in combination with the intriguing site itself, essential criteria for starting a joint archaeological project between Leiden University and the Al-Hussein Bin Talal University in 2011. The Udhruh Archaeological Project started with geographic information system (GIS)-related field surveys and small-scale excavations. This was carried out with the aim of mapping and interpreting the still-visible, standing archaeological remains and of reconstructing the geomorphology of a 48 km^2 landscape in the Udhruh region. Five years of inventory fieldwork (2011–15) revealed an actively exploited region with impressive and ingenious investments in agro-hydrological intensification, in building material procurement, communication and security networks, in military dominion and in settlement development (see Figure 7.1).

Environment and landscape

Udhruh is situated at approximately 1,200 m above mean sea level, and approximately 13.5 km east of the Nabataean city of Petra. Physiographically, the western part of the Udhruh region is located at the eastern edge of the Jabal ash-Sharah. The area is also known as the land of Edom; its height ranges from 1,500 to 1,200 m at the eastern side, extending from the Ras an-Naqb escarpment overlooking the Hisma Desert in the south to the Wadi al-Hasa canyon in the north (Cordova, 2007). The regional part of these highlands is called the Jabal ash-Sharah. The eastern part of the research area is situated in the Eastern Highland Zone.

The Udhruh environs are at the boundary of two climate zones, according to Köppen's classification: cool temperate Mediterranean climate (Csb) on the western side and cool semi-arid climate (Bsk) at

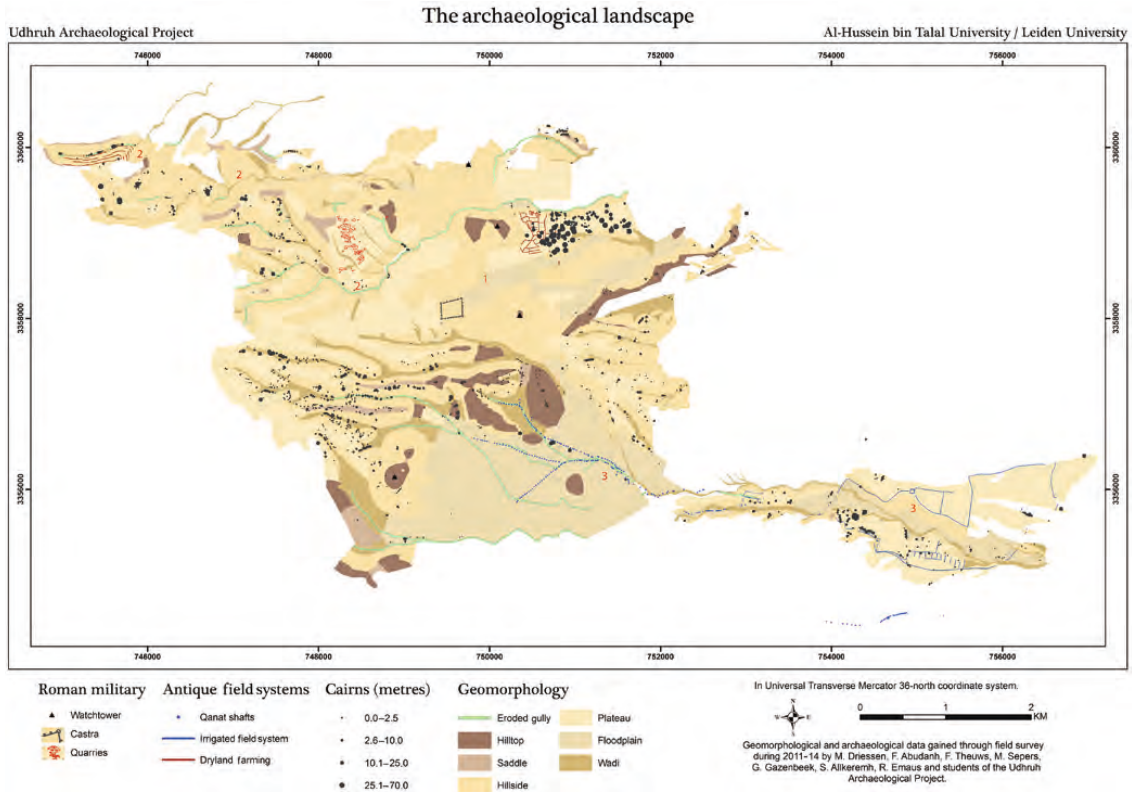

Figure 7.1 Geomorphological map of the 48 km^2 research area of the Udhruh archaeological project, showing only Roman military structures, ancient hydro-agricultural systems and cairns, based on the 2011–2015 field seasons. Three ancient agro-hydrological systems: 1. Plots irrigated by the Udhruh spring. 2. Floodwater harvesting in and towards the Jabal ash-Sharah, with the locations of the three settlements labelled '2' on the map. 3. The Udhruh *quanat* scheme. (Illustration by Roeland Emaus.)

the eastern part of the research area. The mean temperatures range from approximately 10–15 °C in winter to 30–35 °C in the summer period. In the winter it can snow, and temperatures can reach below 0 °C. Conversely, temperatures over 40 °C are not rare in the summer. Nowadays, the Udhruh region receives from 50 to 150 mm of rainfall annually, with higher rainfalls (150–200 mm) in the Jabal ash-Sharah than in the Eastern Highlands (50–100 mm) (Kouki, 2012: 104–5). This precipitation, which is sometimes received in the form of intense but short-lived downpours, falls predominantly in the months of January and February. Because nowadays the wadis lack a man-made control of these downpours, they turn into rapidly changing erosion gulleys. Afterwards the evaporation can be substantial, because of the intensity of the sun and the strong, predominantly dry, western wind coming from the Wādi Arabah (Great Rift Valley). As a result of short-lived cloudbursts, the present-day absence of man-made catchment structures, and the high infiltration capacity of some of the valley beds, only limited amounts of run-off water remain available for, for example, agricultural purposes (Bull and Kirkby, 2002).

From a climatic point of view, we can expect no dramatic changes if we compare the conditions from the Iron Age to the Byzantine period with those in present times, although it would have been more humid in those days than now. A wet phase in the classical period was followed by a drier phase in Islamic times, as was shown for instance in the research in Petra and the nearby Wadi Faynan Landscape Survey (for Petra see Besançon, 2010; for Wadi Faynan see Hunt et al., 2007 and Gilbertson et al., 2007: 406–9; for a wider geographic context see Finné et al., 2011).

The bedrock geology of the region is dominated by Cretaceous and Tertiary limestones. The western ridge towards Petra and the highest part of the water catchment area consist of outcrops of the oldest rock formations: Turonian Wādi As Sir Limestone, a dolomitic limestone deposited in a marine subtidal environment, and the Coniacian–Santonian Wādi Umm Ghudran Formation, deposited as pelagic chalk (Kherfan, 1998). The Wādi As Sir Limestone Formation is one of the highest main aquifers for the region, the topmost of which is several hundred metres below the current surface. More elevated smaller aquifers can be expected in the region, but to locate them specific geo-hydrological research is required. The western part of our research area predominantly contains Amman Silicified Limestone and Al Hisa Phosphorite formations (Santonian–Maastrichtian), consisting of phosphatic chert and limestone, concretionary chert and coquina beds. In some western areas, including Udhruh and the higher eastern parts, Muwaqqar Chalk Marl Formations

(Maastrichtian–Paleocene) dominate, while in the lower eastern areas Pleistocene fluvial, aeolian and Holocene alluvial sediments prevail. Some of the remarkable territorial markers and outcrops in the region – on top of which Nabataean-Byzantine fortlets and watchtowers were located (Driessen and Abudanah, 2013, in press) – are dominated by Umm Rijam Chert Limestone Formations (Paleocene–Eocene).

The main soil types in the Udhruh region are Inceptisols (Xerochrepts) and Aridisols (Calciorthids), while Entisols (Torriorthens and Torrifluents) are found sporadically. In relation to soil fertility and possible plant growth, such Inceptisols tend to suffer from low organic matter and nitrogen contents, while the Aridisols in the (semi-)arid regions of Jordan generally have high salt, gypsum and carbon contents, which makes them not very suitable for cultivation (Lucke et al., 2013: 76).

Literary and epigraphic sources

Udhruh is mentioned in several ancient literary references, from Roman times to the early Islamic period. The second-century AD *Geographia* (5.16) by Ptolemy is the first in which the settlement is called by its local Greek name, *Αδρου*. An early fourth-century building inscription from the legionary fortress at Udhruh does not give us the name of the settlement, but makes it clear that this Roman military camp was rebuilt by the Legio VI Ferrata in AD 303–4 (Kennedy and Falahat, 2008: 159–60). Several Byzantine literary sources tell us that Udhruh became an important town, again under its local names, *Αδροα* and *Αδαρα*.[2] The first one is from the sixth-century Beersheva Tax Edict, which states that Udhruh was assessed for a sum of 65 golden coins (*nomismata*), and thus paid the highest tax of the 18 towns of the province of Palaestina Tertia. The contemporary Stephen of Byzantium (18.18) mentions Udhruh, using its local name, as a large city in this Byzantine province. Udhruh is also known by the honorific name of Augustopolis in several bishop and town lists, relating to the fifth–early seventh centuries (Fiema, 2002: 209–10; it is generally accepted that Udhruh can be identified with the Byzantine Augustopolis; see Abel, 1938; Koenen, 1996; Nasarat et al., 2012: 111). Augustopolis is mentioned in 11 of the 49 Petra papyri.[3] The sixth-century Petra papyri not only make it clear that Petra remained an important administrative centre after the devastating earthquake of AD 551, but they also provide very interesting socio-economic, agricultural and personal information on the region, its hinterland, and the people who lived and worked here. Most of the papyri are contracts relating to the transition of property, mostly real estate, movables and even slaves, through sale, dowry, donation, inheritance and division; and some are juridical documents relating to disputes or registration of assets (Arjava, et al., 2007; Arjava et al., 2011; Frösén et al., 2002; Koenen et al., 2013). The Petra papyri provide us also with detailed information on cultivated crops, allotment sizes, water-management distribution and the different terms pertaining to structures, dwellings and agricultural use. People owned holdings, as well as related houses and structures in Augustopolis and its environs. The papyri also inform us that this Byzantine town was an administrative centre, where properties were registered, sharing the responsibility of tax collection with Petra (see Petra papyri 19, 25, 30 and 31, Arjava et al. 2007). Udhruh remained a prosperous town after the Byzantine period and is mentioned in several Islamic sources (al-Salameen et al., 2011: 239–40). The people of Udhruh agreed to pay a tribute of 100 dinars to Mohammed and his armies in exchange for a peace treaty in AD 630 (Fiema, 2002: 210 and references therein). After the Arab conquest Udhruh had a special position; an important arbitration took place there between competing Muslim parties in AD 657. This resulted in the establishment of the Umayyad state, and 'Adhruh' is mentioned as the major town of the Umayyad province of Ash-Sharah in the eighth century AD (al-Salameen et al., 2011: 233; Fiema, 2002: 210 and references therein).

Ancient water-harvesting methods in the Udhruh region

After five years of predominantly survey and exploratory fieldwork, more detailed archaeological campaigns are planned over the next few years. Three ancient agro-hydrological systems have been distinguished in the Udhruh region (Figure 7.1). These are systems that harvest water from different sources and for different purposes, although agricultural use seems to be the prevailing aim.

The central research question for the project is: What water-harvesting and agricultural adaptations can be observed in the hinterland of Petra that contributed significantly to the transformation and development of this semi-arid landscape in ancient times?

It is our aim through this project to improve the understanding of the hydro-technological innovations and major societal transformations that took place from Nabataean to Islamic times, in the wider region. It has been observed that large parts of these ancient water-harvesting and agricultural field schemes are still largely intact and partly buried by alluvial deposits. An interdisciplinary approach combining archaeological analyses, antique written sources, geophysical, geo-hydrological, socio-hydrological, bioscientific and biogeochemical soil studies will provide us with the necessary data for an integrated analysis, specifically of the ancient water-management and agricultural development of the Udhruh region and the role it played against a local, regional and supra-regional setting.

The following sections present some preliminary results concerning the three water-management systems.

The perennial spring 'Ain Udhruh and associated fields

Udhruh hosted one of the most reliable perennial springs – 'Ain Udhruh – for the entire region. Its water most probably comes from the undulating slopes of the Jabal ash-Sharah and Zebyriyā ridge towards Petra, further fed by tributaries from the Wādī Mulqan and Wādī al-Rumayi, and was transported by aquifers from the Wādi As Sir Limestone and possibly higher-lying formations. This spring was the prime location factor for early occupation, and can be linked to the continuity of human activity pre-dating the Persian period (Abudanh, 2006: 201). Udhruh housed an important Nabataean settlement and most likely developed as a second Nabataean nucleus in the hinterland of Petra, before it was redesigned as a Roman military base (for the Nabataean settlement of Udhruh; see Glueck, 1935: 76–7; M. Killick, 1990; Tholbecq, 2013: 299; Driessen and Abudanah, in press). The Nabataean people did transform the steppe region around Petra into an agricultural landscape consisting of new settlement, water-harvesting and construction works, and arable fields.[4] The beginning of Nabataean sedentary life and agricultural development can be dated to the late second–early first centuries BC (al-Salameen, 2004: 134; Kouki, 2012: 129; Schmid, 2001: 370–1; Stucky, 1996: 14–17). The Udhruh settlement and its perennial source of water were of pivotal strategic importance to the Nabataeans as they constructed an elaborate communication system for the whole region. By the time they had constructed the system, all separate watchtowers and fortlets had a direct visual connection with the higher parts of this settlement (Driessen and Abudanah, 2013, in press). This was, however, a multi-purpose system: it not only applied to military and trade objectives, but also played a role in controlling and safeguarding the newly established agro-hydrological intensifications in and around Udhruh (Driessen and Abudanah, in press). This communication system was kept in use for the protection of field systems established later, during the Roman and Byzantine periods.

The spring of Udhruh was an important factor in the choice of location for the Roman camp (for locational analyses of Roman military sites based on classical sources and archaeology, see Driessen, 2007: 28–35 and tables 2.1–3). In Roman times access to this water resource was at the north-east side of the fortress, where a natural depression leads to the present-day spring. This connection to the spring and to the control of this important water source is most probably the reason why this side of the *castra* has an atypical trapezoidal shape. Another unusual feature that struck us immediately was the slope on which the fort was built. These somewhat odd characteristics were necessary both to incorporate the source of water, and to provide a territorial marker connecting to all the watchtowers in the surrounding region. The layout of the fortress, therefore, was thought out very well. The towers were constructed with the intention that they would withstand potential earthquakes, and with measures to enable good air circulation. There were even large cisterns in some of them. The south-east corner tower used to house a large antique cistern, which was in use until recently, when it was closed because of the risk to playing children. A cistern excavated by us in part of the eastern gate towers was covered up again for the same reason a few years ago.

In an aerial picture taken in 1939 by Sir M. Aurel Stein, a system of well-watered and dark-coloured allotments, probably compound gardens, is observable at the north-eastern side of Udhruh's Roman fortress (see Figure 7.2). The visible network of water-distribution channels, diversion structures, barriers and even spillways gives a good impression of how the system must have operated in those days. Three other aerial pictures, taken on 11 April 1939, do not show any more houses or dwellings than those visible in Figure 7.2. This corresponds with the results of our oral history project, through which elderly members of three extended Udhruh families told us that they all held several agricultural allotments here, while still living a predominantly semi-nomadic Bedouin lifestyle. The 'Ain Udhruh spring dried out in the 2010s, but was used as a source of water distribution to feed (via still visible channels) the field systems east of Udhruh. In 2014 we saw this water-distribution system in operation for the last time, no longer fed by the ancient spring but through a modern water supply system. The distribution was the responsibility of the men, who worked out a water-management schedule at the community level. 'Ain Udhruh is considered of high importance because of its creation and maintenance of a shared sense of identity and spiritual meaning for the people of Udhruh (Hageraats, 2014). The spring fell dry as the result of a combination of changing climatic conditions, sinking groundwater levels and, according to local people, construction failures

Figure 7.2 Aerial picture of Udhruh (taken on 11 April 1939). On the left the Roman fortress of Udhruh and on the right irrigated plots (picture by Sir M. Aurel Stein: APAAME_19390411_Stein-BA-ASA-3–0510, Aerial Photographic Archive for Archaeology in the Middle East)

by the government when they built the nearby road. The groundwater levels will be further lowered by recent attempts at 'hit-and-run agriculture', a problem that is noticeable over the whole region. This consists of pumping up excessive quantities of very deep underground water for watering annual food crops. We call it 'hit-and-run agriculture' because it is definitely not permanent, nor sustainable, and the growers seem to be interested only in a quick profit. Some of the more fertile soils were selected for this activity for large-scale one-year cultivation sites; an enormous waste of precious water appeared to take place, probably resulting in serious salinisation of the soils.

Till 2014, when the irrigation scheme fed by 'Ain Udhruh was in operation for the last time, we thought it inappropriate to venture into these fields for our archaeological field surveys. We asked local permission in the following years, however, to do some pilot surveys and have a closer look at the scheme. From these it became clear that older stone walls and bunds were laid out under and next to the more recent structures. We have distinguished 127 of these older allotments so far, varying in size from 275 to 5,500 m^2 and covering a total area of 0.735 km^2. In these fertile plots we encountered several concentrations of ceramics, dating predominantly to the Nabataean, Roman and Byzantine periods, and mainly located at the northern and eastern elevated boundaries of the small valley. We also picked up several pottery fragments of the same periods when surveying across the field system. The dating of this material culture corresponds to the major settlements of Udhruh in antiquity, and their spatial correlation with the perennial spring. These observations make it very plausible that this fertile land was used in antiquity for orchards or compound gardens. Such field, irrigation and water-distribution techniques were widely practised in the Petra region in the Nabataean period. Several archaeologists have noticed that the Nabataean irrigation structures were often reused in later periods, and some are still in use by local communities (al-Muheisen, 2009: 142–3; Beckers et al., 2013: 346–7; Beckers and Schütt, 2013: 321; ‘Amr et al., 2000: 234, 239; Kouki, 2012: 108, 123–5; Nasarat et al., 2012: 107–9). It is not only archaeology that shows that Udhruh and its environs were turned into a prosperous agricultural region. The literary sources provide us with intriguing examples as well, especially for the Byzantine and early Islamic periods. In the light of this the Petra papyrus (39) is of special interest. It describes a dispute between two neighbours in a nearby settlement over water-draining rights from a spring and the theft of building materials and the construction of water channels (Arjava et al., 2011: 48–56). These include structures containing intact mortar samples that include charred twigs, which we intend to use for 14C dating.

Flood-water harvesting in the Jabal ash-Sharah

The best conditions for cultivating crops in the hinterland of Petra are to be found in the Jabal ash-Sharah area (Besançon, 2010: 42). This is the area west of Udhruh and is characterised by a landscape with gentle slopes interspersed with wadis.

Settlements

During our field surveys we encountered three ancient settlements in the Jabal ash-Sharah area. The first is located 2.3 km west of Udhruh, in the Wādī al-Harab, north of the Udhruh–Wadi Musa road (this is site no. 27, called Wādī al-Harab in Abudanh, 2006: 411). The settlement is built on the slopes of a curved tributary of two wadis, where a diversion dyke with connected conduit walls was built, probably to avoid water damage in the rainy season. The large settlement, of about two hectares, is surrounded by low enclosure walls, and is occupied by some traditional houses which were reportedly built in the mid-twentieth century by Sheikh ʻAbd Allah Dhyab Harb Al Jazi, who was about 90 years old when the authors interviewed him in 2014. These houses were built on older foundations that lie underneath a dense layout of dwellings and other structures that fill the northern side of the settlement. Two cisterns and four threshing floors were uncovered on the northern slopes of the settlement. One cistern was inaccessible, but the other one (7.2 m long × 3.5–4.8 m wide × > 3 m high) had a cover stone with a neatly cut square opening, and was found to be plastered with a remarkable mortar lining. The mortar contains fragments of Nabataean pottery, and resembles the mortar linings found in several structures in Petra, like those of the water basins of the 'Garden Temple' complex. The threshing floors are mostly oblong-oval in shape (roughly 6 ×16 m, 8 × 27 m, 12 × 29 m and 14 × 28 m), and have low dry-stack sidewalls on the southern wadi sides. They also seem to be determined by the existence of natural flat outcrops. Such threshing floors are impossible to date, but are found at other archaeological sites around Petra and are mentioned in the Petra papyrus 17 (Abudanh, 2006: 203; Fiema, 2002: 205–6; Frösén et al., 2002: 312–13; Glueck, 1935: 74–5; Koenen, 2004: 355; Koenen et al., 2013: 1–2, 107, 126–7, 142). Intensive surveys of this settlement – an area of over 61,200 m^2 and with a grid of 20 × 20 m blocks – produced almost 1,200 ceramic surface finds (Table 7.1), which can be assigned to the Nabataean, Roman and Byzantine periods.[5]

Two other settlements were uncovered in the more westerly part of the research area (Figure 7.1) that contained house structures comparable to the ones found in the first settlement.

Pilot surveys at these settlements and in surrounding fields revealed ceramic sherds, predominantly Nabataean. The assemblages also revealed a decline in ceramics in the late Roman period, but with an upturn in the Byzantine period (Wenner, 2015: 137–65).

Table 7.1 Ceramic evidence (number of sherds per period) of intensive surveys at Wādī al-Harab settlement

Nabataean	Nabataean-Roman	Roman	Roman-Byzantine	Byzantine
435	302	141	37	145

Run-off water harvesting

The slopes and valleys of the wadis in the western part of the research area (the Wādī al-Harab, the Wādī Zubayra, the Wādī al-Rumayi, the Wādī Mulqan and its tributaries) are covered with structures relating to a combination of, or adjacently operated, hillside conduit and flood-water farming systems. Terrace walls and conduit channels were constructed on hillsides in order to collect and direct the run-off rainwater to the connected levelled fields on the lower slopes and the bottoms of the wadis. At the bottom of the wadi beds west of Udhruh many dams and dykes have been uncovered. Several dams, whose lengths varied between 15 and 130 m to match the width and depth of the valley bottoms, were neatly built at irregular distances in almost every wadi that we surveyed. The surviving height of these dams was never more than 1.5 m, but on some the original spillways could be distinguished. Such dams were probably constructed both to reduce the water velocity after the intense downpours of the rainy season, and to collect this water. But they probably also encouraged eroded sediments to settle and thus improve the arable land in the wadi-bed (see Oweis et al., 2012: 58–62, 66–9 for such systems, which are still employed today). These wadi-bed water-harvesting and hillside conduit systems (with both macro- and micro-catchments) have also been found at other archaeological projects in the Petra region, including in the Wadi Faynan and in the Negev (for the Petra region, see Alcock and Knodell, 2012: 7; Beckers et al., 2013; ʻAmr et al., 1998; Lavento et al., 2004: 166–7; Urban et al., 2013; for Wadi Faynan, Newson et al., 2007; for Negev see Bruins, 1986). The dating of these schemes is complicated by a lack of directly associated dating material, possibly by use over a very long period, and by the fact that similar structures are used for current agriculture. From the dating of ceramic finds from the fields integrated in or adjacent to these wadi-bed water-harvesting and hillside conduit systems, and the dating of nearby settlements, a Nabataean origin can be suspected. Our field surveys also lead us to expect that these flood-water-harvesting systems in the Jabal ash-Sharah region experienced an increase in the Byzantine period. OSL and radiocarbon dating were employed, by another research team in the vicinity of Petra, on samples from several similar agricultural terraces. This took place in the Wadi al Ghurab catchment area, and the results suggested a Nabataean origin with a possible continuity of use until the eighth century AD (Beckers and Schütt, 2013: 321; Beckers et al., 2013: 346–7). These results are similar to our analyses of the ceramic assemblages for the Udhruh region. We were initially reluctant to apply these scientific dating techniques to dams and walls, as we noticed many cases of natural undercutting and backfilling. We will, however, continue our search for intact interiors inside standing dams and terrace walls. This is because we think that using samples from such contexts diminishes the risk of post-dating errors. The Udhruh surveys were initially started to reconstruct the geomorphology of the landscape and to provide GIS-related locations of all (old) man-made structures. More detailed information has been gathered over the last few years by measuring 3D-points, angles and distances between the structures. This includes the measurement of hillside conduit and flood-water-farming systems, nearby settlements and the related landscape, using Total Stations and a 3D-scanner.[6] With these results it is planned to make modelling calculations and then reconstructions of the hydrological capacity, abilities and effectiveness of the systems in several locations (the side-arms and catchment areas of the Wādī al-Harab, Wādī Zubayra, Wādī al-Rumayi and Wādī Mulqan).[7]

These flood-water-harvesting schemes were probably used for cereal cultivation. This main staple fits well with the large-scale set-up on all hillsides for a whole region, the seasonal water availability, and the evidence from the excavated threshing floors. Sampling for archaeo-botanical and pollen analyses is not useful here, however, as these fields are still regularly used for cereal growing by local Bedouin families. This is also true of similar ancient run-off water systems for the wider regions (Alcock and Knodell, 2012; Beckers et al., 2013; Bruins, 1986; ʻAmr et al., 1998; Lavento et al., 2004: 166–7; Newson et al., 2007; Urban et al., 2013). Dozens of quernstone fragments used for milling grain have been found during surveys in the research area. Such grinding stones were retrieved from Roman-Byzantine archaeological contexts, but also as surface finds. The problem is that these stones were also used by Bedouin throughout the nineteenth and twentieth centuries, and it is difficult to distinguish the later ones from the ancient ones.

These water-harvesting systems in the Jabal ash-Sharah part of the research area were employed to hold and redirect run-off water that would otherwise have been lost. However, these systems do not allow for a more continuous agricultural crop rotation, as the captured and diverted water would only be available for a limited period of time after the seasonal precipitation. In antiquity solutions were also employed to make use of deep percolation water that would otherwise be lost and to prevent evaporation, as will be illustrated in the following section.

The Udhruh *qanat* and connecting field systems

To the south-east of Udhruh lies an impressive network of well-preserved ancient subsurface and surface-water conservation measures and connected irrigated fields – a *qanat* system – was recorded in a large floodplain largely covered by alluvial deposits (Figure 7.1) (for earlier observations of structures related to this *qanat* system see Abudanh, 2004: 488–489, 492–493; 2006: 71–81; Abudanh and Twaissi, 2010: 69–70; A. Killick, 1987: 28; Stein, 1940: 435). *Qanats* were most probably first used in the Armenian-Persian region, date back to around 700–600 BC (Lightfoot, 1996: 324), and are the subject of many other studies. The Udhruh *qanat* consists roughly of three components: 1) the subterranean water system consisting of vertical *qanat* shafts and horizontal underground water conduits; 2) the surface part of the water system comprising outlet(s), channels, distribution structures and large reservoirs; 3) agricultural field systems with irrigation channels.

Subterranean structures

For the subsurface part, three lines of vertical *qanat* shafts (totalling more than 200 individual shafts) were dug and hacked out of the limestone bedrock, 1.1–3.9 km south-east of the fortress of Udhruh. These shafts are currently filled in, and recognisable by circular mounds or hollows, probably created during the construction and maintenance of the shafts, and later filled in with blown- or filled-in debris. We have already counted 243 of these circular mounds, positioned at regular intervals of about 25–30 metres apart. There must have been more though, as some parts of the lines lack such mounds and some shafts are losing their surface visibility as a result of erosion and modern cultivation. At the western side – near Tell Abara – the *qanat* tapped into three or four ‘mother wells’ which are probably fed by groundwater from elevated aquifers. A modern water station is situated to the west of Tell Abara and close to the mother well in the southernmost line of shafts. We noticed over several campaigns that a small but continuous flow of pulsating water was coming out of a surface pipe near this station, which was probably drilled into the subterranean water level. Therefore it is assumed that the aquifers must still contain water. The three lines seem to merge near the modern Udhruh-Ma’an road approximately 2.8 km south-east of Udhruh. This intersection is uncertain, however, because of the observable distortions in this area, and further east two parallel lines of shafts are seen heading towards the Wādī el-Fiqay. Along with construction and maintenance purposes, the shafts play an important role in ventilation of the *qanat* (for such use see Lambton, 1989: 7). The horizontal underground tunnels of the Udhruh *qanat* have not been investigated yet, as the vertical shafts are filled in. One of the men we interviewed from Udhruh told us that some of the shafts near the Udhruh-Ma'an road were still (partly) open a few decades ago. But because someone fell in and was killed they were backfilled. A start has been made on the archaeological excavation of one vertical shaft, which was stopped unfortunately after four metres because we reached the maximum depth with the ladders we had available. It was already clear that the more or less square shaft (about 2 × 2 m) was cut through the Muwaqqar Chalk Marl rock formation, with evenly distributed man-made holes in the opposite walls, which were probably used to hold bars for a ladder construction. A large tripod and military rope hoists will be used to further excavate this *qanat* shaft. Soil samples will be taken to date the period during which the *qanats* went out of operation, and also for micro-morphological research in order to find out if the backfilling started through natural processes or anthropogenic activities. Reaching the bottom of this shaft will also allow us to access and gain knowledge about the horizontal tunnel and channel construction, hopefully with datable material culture and mortar samples. The aim is eventually to excavate at least one 'mother well' shaft and two other additional shafts to obtain data, especially on the hydrological capacities of the channels. Research at other *qanats* makes it clear that the gradient of the shorter conduits varies from 1 to 5 per mille, while longer ones are almost horizontal (Lambton, 1989: 7). Our observations of the surface parts of the Udhruh *qanat* show that a gradient of less than 2 per mille was utilised for this. The *qanats* with such a gradient not only provide a steady year-round flow of non-turbulent water, but also furnish another advantage: evaporation from these subsurface conduits is limited.

Surface constructions

The subsurface parts of *qanats* transport water from a mother well to a surface outlet. After travelling 3.1–4.5 km through underground conduits, the water probably reaches a surface outlet. An erosion gully in the alluvial deposits of the Wādī el-Fiqay unearthed two parallel surface channels of different construction only 200 metres from the most north-eastern *qanat* shaft. An outlet point can therefore be expected somewhere in these environs. The surface parts of the water scheme in this wadi are covered with thick alluvial deposits in some places, while at other spots they stand above the current ground level. The surface water conduits – with total lengths of 1.9 and 2.6 km – end at two large reservoirs connected to agricultural field systems. Figure 7.3 uses actual field observations to show the current state of research. The two parallel surface channels seem to be pivotal in this agro-hydrological scheme. One consists of two straight side walls (0.2–0.3 m wide) made of roughly cut limestone blocks with a floor of the same material, creating a 0.35 m-wide and 0.9 m-high conduit. A channel with similar dimensions and layout was found in a 3 m-deep erosion gulley (this is the point with water-level height of 1,001 m in Figure 7.3). At this location it became clear that this channel was originally covered with slabs of brecciated chert. This was done to prevent the channels from silting up with alluvial, colluvial and aeolian deposits, to reduce the evaporation of the transported water, or a combination of the two. This covering made the interior dimensions of the water channel clear. The second channel is made up of two parallel 0.5–0.6 m-wide and 0.65 m-high side walls of concrete and large limestone blocks, on top of a 2.3 m-wide and 1.5 m-high foundation of the same construction. The water conduit itself, 0.4 m wide and 0.55 m high, is made up of a perfectly smooth 3–4 cm-thick mortar lining. A channel of similar layout was partially excavated in 2016 (Figure 7.4).

Two large reservoirs were constructed at the eastern end of the water-harvesting and transportation scheme. The most northern 50 × 50 m reservoir – with standing walls still up to 1.5 metres – was partly dug with 2.5–3 m-wide earthen ramparts, probably to withstand the internal water pressure. The side walls are made up of large cut coquina blocks, resembling in size and provenance the ones applied to the curtain wall of the Roman fort, upon which a 0.3 m-thick layer of larger stones filled up with mortar and charred particles was placed. A 7–8 cm-thick concrete lining which included small rounded pebbles and pottery fragments was applied to make it waterproof. Measuring the lower water levels of the different structures (see Figure 7.3) also enabled the capacity of the reservoir (which has an inside surface area of 2,238 m^2) to be calculated: it comes to a maximum of about 3.3 million litres of water. The southern 34 × 33 m reservoir was dug into the slope of a small hill (on the northern, western and southern sides). The dry-stack side walls of this reservoir are still standing up to 2.7 metres high; they were made of large limestone blocks plastered with a 3 cm-thick concrete lining. The same plaster lining, to which red pottery fragments and small pebbles were added, was also applied to the bottom of the reservoir. On the eastern side an earthen rampart, with special reinforcements, which proved to be part of later renovations, was added to prevent this side from collapsing as a result of the water pressure. The maximum capacity of this reservoir (with an inside surface of 988 m^2) was about 2.7 million litres of water.

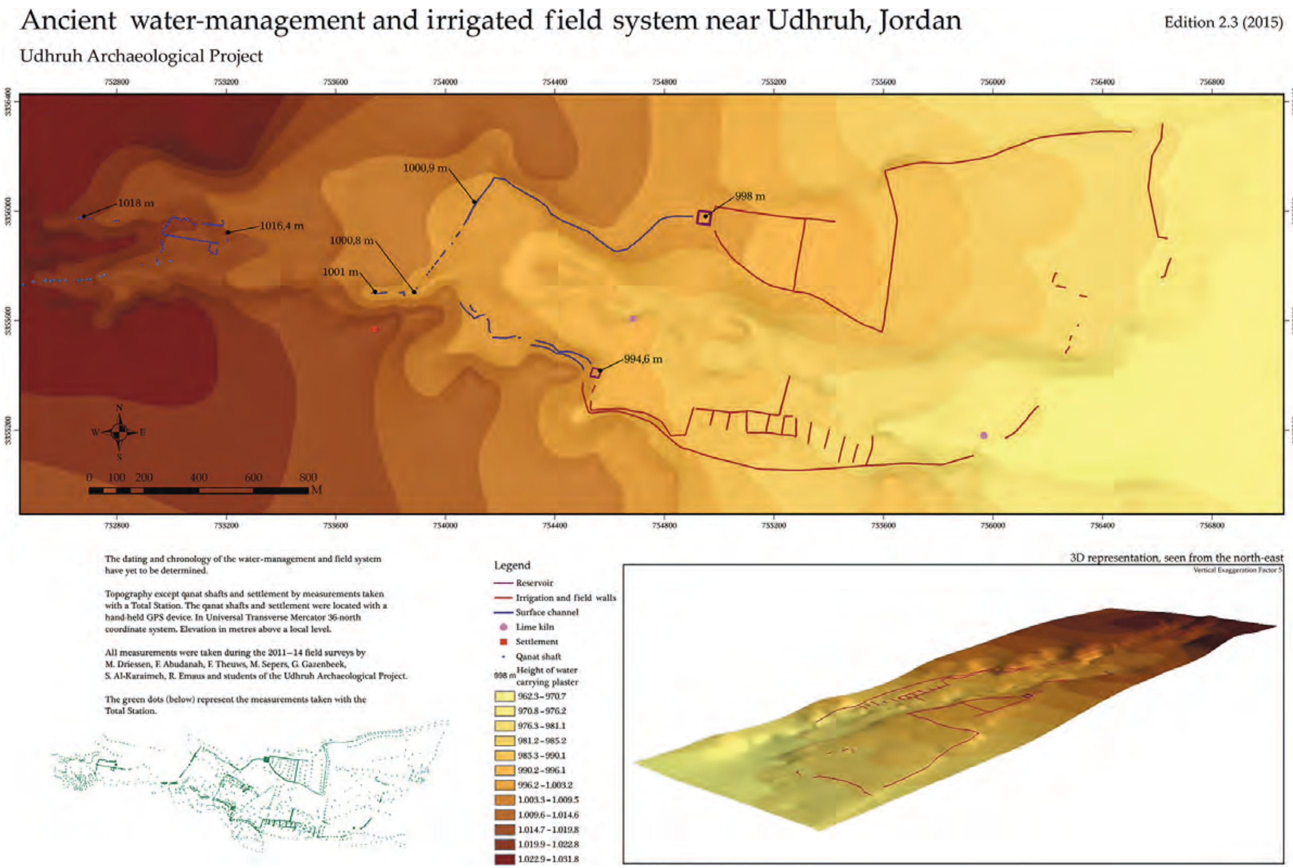

Figure 7.3 The ancient water-management and irrigated field systems in the Wādī el-Fiqay, which is fed by the Udhruh *qanat* system (drawing by Roeland Emaus)

Figure 7.4 3D reconstruction of a surface channel of the Udhruh *qanat* scheme (drawing by Maarten Sepers)

No features were found that may relate to the reduction of evaporation from these large open water surfaces. The basic concept of the water cycle was already understood in classical times, and the evaporation of rainwater was a known concept mentioned by Hippocrates in the fifth century BC.[8] It seems logical that measures against evaporation were installed, especially if one considers all the effort and investment that were already made to get the water here. These, however, do not have to consist of a complete roofing; effective precautions, archaeologically almost or completely untraceable, may have been applied.[9]

By means of small-scale excavations, together with aerial pictures, 3D-scanning, and non-destructive, geophysical, ground-based and air-borne exploration methods, we plan to complete the survey of the lay-out of the surface part of the water transportation system.[10] Regarding the non-destructive, ground-based techniques, some initial work with a ground-penetrating radar (GPR) and a magnetometer have been carried out with promising results. These results have already revealed some new information on the layout of the scheme, revealing, for instance, the dimensions of a third reservoir (14 × 14 m). The construction of the reservoir walls and the typical form of the lower outlet on the eastern side make it clear that this reservoir had a dual function: water distribution and water treatment through sedimentation.

Many different types of mortar came to light during the surveying and excavation of the different structures of the hydrological scheme in the Wādī el-Fiqay. The mortar linings of the reservoirs and channels are solid, smoothly finished and loaded with small rounded pebbles and small ceramic fragments, which make the linings strong and waterproof. The foundations of the large reservoirs were made of larger stone blocks held together by loamy mortars with included charred wood and twig particles. These were applied to create a solidity or sturdiness able to withstand the pressure of large quantities of water. The mortars of the channel foundations, on the other hand, are lightweight, with elastic properties, and seem to be made to withstand tensile forces. We encountered at least nine different types of mortar. It seems that people were making these mortars with different physical capacities for different purposes; of these, the very elastic mortars were the most remarkable, and were probably used in a trial to withstand the earthquakes that ravaged these regions in antiquity.[11]

Two large lime kilns were located (Figure 7.3) that shed light on the mortar production for the construction, maintenance and renovation of the conduits and reservoirs. Vast amounts of combustibles were needed for the lime-burning process to make these mortars. Heaps of ashes and charcoal particles near the kilns – with a diameter of around 10 m – may suggest that firewood was used. Intensive surveys on and around the fields provided us with a wide variety of material culture. This includes several Upper and Middle Palaeolithic hand-axes, blades and arrowheads, together with substantial amounts of Nabataean, Roman and Byzantine pottery, smaller quantities of early Islamic and Ottoman pottery, fragments of Mamluk glass bracelets and a wide variety of remains from the Great Arab War. This broad spectrum does not help us to get a balanced, well-founded grip on the chronological framework, but it makes it clear that people have been using this area for vast periods of time. The ceramic evidence from pilot surveys at a nearby settlement – Khirbet el-Fiqay (Figure 7.3) – shows high usage during the Nabataean, Roman and Byzantine periods, with possible reuse during Ayyubid-Mamluk times.[12] This settlement is located 1.0 and 0.6 kilometres – as the crow flies – from the northern and the southern reservoirs respectively. Its position is around 10 metres higher than the nearest channel, which was found 50 metres away in the erosion gully. No other settlements have been found near or next to the reservoirs and fields, so uses for the *qanat* system other than for agricultural purposes can be excluded at this stage. The OSL dating of the mortars used for the two large reservoirs shows that the northern reservoir was built during the Nabataean period, with adaptations or renovations in Roman times (Table 7.2). The southern

Table 7.2 OSL and 14C dating of Udhruh *qanat* reservoirs in Wādī el-Fiqay (OSL datings by Alice Versendaal and Jakob Wallinga (Centre for Luminescence Dating – Wageningen University; 14C datings by Hans van der Plicht and Sanne Palstra (Centre for Isotope Research – University of Groningen))

Feature description	Feature number	Sample number	Palaeo-dose (Gy)	Dose rate (Gy/ka)	Age (ka)	Model	Comments	Date (from OSL)
North reservoir – mortar lining bottom	9001	875	3.00 ± 0.12	1.69 ± 0.06	**1.78 ± 0.10**	Iterative	Fraction 180–212	237 AD ± 100
North reservoir – mortar lining S wall	9001	876	1.37 ± 0.03	0.78 ± 0.04	**1.77 ± 0.09**	Iterative (1.5 SD)	Fraction 63–90	247 AD ± 90
North reservoir – mortar lining wall SE corner	9001	1450 – 1451	3.05 ± 0.14	1.46 ± 0.06	**2.09 ± 0.13**	Iterative	Fraction 90–250	73 BC ± 130
North reservoir – basic layer bottom	9001	884	3.01 ± 0.28	1.53 ± 0.06	**1.97 ± 0.20**	MAM	Fraction 90–250	47 AD ± 200
South reservoir – mortar lining wall SW corner	9479	1440	3.37 ± 0.10	1.84 ± 0.07	**1.83 ± 0.09**	Iterative	Fraction 90–250	187 AD ± 90
South reservoir – wall NE corner – upper part	9479	1441 – 1444 – 1445	3.12 ± 0.21	1.87 ± 0.14	**1.66 ± 0.17**	MAM	Fraction 90–250	357 AD ± 170
South reservoir – renovation/enforcement NE corner abutment	9479	1453			**1.325 ± 0.03**			655–90 AD / 750–76 AD (14C)
South reservoir – renovation/enforcement NE corner abutment	9479	1447			**1.4 ± 0.02**			630–60 AD (14C)

reservoir was of later date; it was constructed during Roman times with adjustments in the late Roman or Byzantine period. The 14C analyses of charred twigs found in the mortar of a later outer reinforcement from the southern reservoir show that this was accomplished in the Umayyad period. An analysis of the scientific dating in relation to the material culture makes it clear that a Nabataean-Roman origin, with later reuse in late Roman, Byzantine and Islamic times, is quite plausible and fits with the broader picture.

Agricultural fields

This subtle system for harvesting deep percolation and groundwater is designed to irrigate an extended agricultural field system with at least 35 hectares of tilled land, east of the reservoirs. Two large fields (approximately 20 hectares in total) connected to the northern reservoir are still completely level with surrounding walls. These walls were used as water conduits. Older and more recent aerial pictures reveal a delicate chequerboard pattern within these fields, a possible indication of a regular block field system. In more recent times, such field systems in the Iranian Plateau are seen as the result of more efficient irrigation methods and agricultural intensification, arising from increased population pressure (Bonine, 1989: 35–8).

Next to the southern reservoir we found an old field of about 4 hectares, with a connected field system of 10 smaller terraced fields ranging in size from 2,800 to 5,400 m^2. Some of the walls or dams between these fields still have visible spillways. The smallest of these plots is of particular interest because the size is about the same as the 1⅑ *iugerum* well-watered field sold by Theodoros to Philoumenos somewhere near Udhruh in January AD 559, as mentioned in the Petra papyrus 25.

The tilled fields of the northern reservoir were connected to those of the southern reservoir by a surrounding enclosure (Figure 7.3) – east of both reservoirs – comprising an area of more than 1.5 km^2. Although the northern reservoir was of Nabataean construction, at some time in the Roman and Byzantine period the *qanats* and connected fields became part of one large agro-hydrological scheme, covering a total area of more than 6.5 km^2, that made use of water that would otherwise have been lost because of deep percolation. Water was protected from evaporation so that it could be accessed not only for a few months of the year (just after the rainy season), but also more continuously over longer periods. This system allowed for differing kinds of agricultural crop rotations (resulting, for example, in more than one yield of cereals a year), or irrigated the fields for newly introduced perennial plants. This must have led to a serious agricultural transformation, with new farming strategies and equivalent technologies in processing and handling. It must also have affected the human agents, thinking only of changes in the seasonal life cycles of the communities involved. Such a large scheme as this can only be part of a programme of agricultural intensification: its scale and technical innovations point to an authority with means, vision, labour capacity and level of organisation, the Roman state for instance. It is tempting to look, therefore, at a nearby Roman legionary fortress, also constructed with great ingenuity, that housed more than 1,000 well-trained soldiers – young men whom one does not want to sit idle, as ancient literary sources provide plenty of examples of Roman military mutinies, the result of boredom and idleness among the troops.

We were eagerly anticipating finding out what crops were grown in the ancient fields watered by the *qanat*, and what the background vegetation looked like. Samples were taken for archaeobotanical and pollen analyses. Several samples from the northern fields were processed. Unfortunately, they contained neither macrobotanical remains, nor pollen, nor non-pollen palynomorphs.[13] More samples will be collected, however, and processed, as some mortar samples have provided us with exciting macrobotanical remains like grape and almond seeds. In the meantime, clues about the cultivated crops might be retrieved from artefacts such as the already described quern and milling stones, which were also found in this part of the research area. A cylindrical crushing roller (diameter 1.02 m and width 0.41 m) made of very hard limestone, showing marks of continuous rolling, was found in the centre of the Roman fortress of Udhruh. Such rollers, which formed part of olive oil presses, have been found in predominantly Roman and Byzantine contexts, although some Nabataean and Ottoman contexts have also been identified (Frankel, 1999; Kouki, 2012: 109).

Interdisciplinary approaches

The two main soil types of the Udhruh region (as seen in the subsection 'Environment and landscape', above) bear some negative characteristics that make them not very suitable for agriculture. The sections presented above make it clear that investments of great effort, ingenuity, knowledge and experience were made to plan and construct the Udhruh *qanat* system. The many kilometres of long subterranean and surface water channels, together with connecting reservoirs, would not have been built here if the soils of the related fields had not been suitable for cultivation. Further tests are planned to find out more about the chemical soil quality and characteristics. Two soil samples taken from the fields east of the northern reservoir have already been analysed as a preliminary test for such characteristics.[14] The result for electrical conductivity shows that these samples have low salinity levels, and therefore no restrictions on plant growth are to be expected. The soil pH (KCl) is about 8, only slightly above the optimum for many plant species. Soil N (primarily as organic N) and Soil P are high when compared with the values expected for this area, although the latter tends to decrease with the depth. Most of the carbon in the samples is present as inorganic C, but the organic C is (still) high compared with soils typical of this climate and landscape. The organic component is quite old and probably consisted of recalcitrant organic matter, as was shown by the soil C:N ratios. These results correspond with archaeological data that suggests that these fields were not used for agriculture throughout the last centuries. The oral history project underlines this as well. During a 2014 site visit, the 90-year-old Sheikh ‘Abd Allah Dhyab Harb Al Jazi told us that these fields were not cultivated by his ancestors, and, according to his oral tradition, nor were they by the Ottomans. These soils – according to him – are too hard to work, and could have only been cultivated by the ‘Romani’. Archaeological surveys show that the Ottoman water piping from Udhruh did reach to other fields quite remote from the field systems we investigated. Concluding the results for these still very preliminary soil tests, it was stated that, ‘[e]ven though the old organic matter is expected to be resistant to further decomposition, recent research has shown that an external source of labile organic matter, e.g. fresh plant litter, may “prime” old organic matter and release nutrients like N and P through mineralisation’. The preliminary results of the soil analyses are therefore promising, and justify further research into the extent to which they apply to all the ancient agricultural fields in the region. This research raises the question of how to revive these soils for possible future use.

In order to obtain a well-founded insight into the hydrological capacities of the *qanat* system, we must measure all the ancient water levels and dimensions of the structures, together with the fields. A pilot study had already been undertaken, which calculated the abilities of the system to provide enough water to the related fields. This made a set of assumptions about evaporation, infiltration, seepage and roughness coefficient. Several scenarios were prepared that made use of the AquaCrop, the crop growth model developed by the Food and Agriculture

Organization (FAO) of the United Nations.[15] This preliminary research already shows that the system worked properly; that is, the *qanats* must have been able to provide a water flow rate which was more than adequate to irrigate the connected field systems.

Conclusions and future research

A large part of the unevenly distributed annual rainfall in arid and semi-arid regions gets lost without becoming available for agricultural use. Most of this loss is the result of evaporation (30–50 per cent), run-off (10–25 per cent) and deep percolation (10–30 per cent). In antiquity different techniques of water collection were already being applied in order to decrease such water loss.

The well-preserved ancient landscape around Udhruh shows that such techniques were being practised in this region; water-harvesting measures relating to run-off loss were already employed in the hilly Jabal ash-Sharah. These harvested waters were probably used for cereal production, and had an origin in Nabataean days but experienced an increase in the Byzantine era.

The Udhruh *qanat*, with its related field scheme, is probably one of the best-preserved field 'laboratories' for the study of the long-term development of innovative water-management and agricultural systems in southern Jordan. It is also one of the most complete *qanats* in the wider region, and one that has not been modified for some centuries, as can be observed at other examples in Syria, Iran and Saudi Arabia. It has its origins in the first century AD, then develops into a programme of agricultural intensification in the following centuries, making use of water that would otherwise have been lost as a result of deep percolation. Water thus became available throughout the year, which must have led to the development of other farming strategies, together with newly introduced perennial plants, changes in processing technologies, and transformations in the seasonal life cycles of the communities involved. This state of affairs could only have been established under the supervision of a central authority with adequate vision and technical background, an authority that was able to control and organise the required means and labour. The system was probably very successful, as it was renovated and adjusted in the Byzantine and Umayyad periods and eventually covered a time span of at least six centuries. The long-term use of such a system was only possible if people were practising what is nowadays labelled sustainable agricultural and hydrological management. Overwatering, as observed in so many current irrigation schemes, would have led to detrimental salinisation of the soils and short-term use. Trying to unravel the exact *modus operandi* of this *qanat* scheme and its long continuity of use will be one of the greatest challenges for our research project in the coming years. This can only be accomplished by practising an interdisciplinary approach in which archaeological research is integrated with historical, geophysical, geo-hydrological, socio-hydrological, bioscientific and biogeochemical soil studies. On the one hand we think that this approach will help us to reconstruct the development of the agro-hydrological landscape in the Udhruh region over the *longue durée*. On the other hand we hope that the interdisciplinary approach – the first author is both an archaeologist and an agronomist – will not only result in a better comprehension of the ancient, semi-arid landscape management strategy from a diachronic perspective, but also lead to translational and innovative thinking, which may contribute to sustainable agricultural and water-management solutions for future use in these regions.

Acknowledgements

The Udhruh Archaeological Project and the preliminary results in this paper would not have been possible without the hard work and assistance of our team. The Project's core team consists of Roeland Emaus, Guus Gazenbeek, Sufyan al Karaimeh, Maarten Sepers, Frans Theuws, Sarah Wenner, Fawzi Abudanah and Mark Driessen. We would also like to thank all the students who participated in the project, and all the researchers who provided us with new and additional results. We sincerely hope for a continuing academic relationship with them and all our other partners, and would like to additionally thank the following: Alice Versendaal and Jakob Wallinga (OSL dating – Wageningen University), Hans van der Plicht and Sanne Palstra (14C dating – Groningen University), Maurits Ertsen (hydrology and water resources management – Delft University), Dominique Ngan-Tillard and Martijn Warnaar (GPR – Delft University), Khaled al-Bashaireh (stone provenance determination – Yarmouk University), Marcel Hoosbeek and André van Leeuwen (soil quality analyses – Wageningen University), Joanita Vroom (Byzantine–early Islamic ceramics – Leiden University), Willem Willems† (CS – Leiden University), Mohammad al-Marahleh and Aktham Oweidi (Department of Antiquities, Jordan), and of course the people of Udhruh. Our gratitude also goes to the APAAME team of David Kennedy, to Fenno Noij and Marcus Roxburgh for their assistance in editing, and to Mark Altaweel and Yijie Zhuang for the invitation to participate in the conference 'Comparative Water Technologies and Management: Pathways to Social Complexity and Environmental Change'.

Notes

1. The Nabataean period in this region traditionally dates from the third to the second centuries BC till AD 106, the date of the establishment of the Roman province of Arabia, although the material culture and layout of structures remain dominantly Nabataean through large parts of the second and third centuries AD. For earlier expeditions and research in Udhruh, see, for example, Brünnow and Domaszewski, 1904: 429–62; Glueck, 1935: 76; M. Killick, 1990: 249–50.
2. Respectively from the Beersheva Edict (Segni, 2004: 151–2) and Stephen of Byzantium (18.18).
3. Augustopolis is mentioned in papyri 3, 7, 8, 9 and 10 (Frösén et al., 2002: 19, 25, 30, 31, 32, 36; Arjava et al., 2007, but it must be noted that not all of them are well enough preserved to provide such geographical information).
4. Diodorus Siculus (1979: 2.48.3–4) says of the Nabataeans that they have strategically located and hidden wells, and Strabo (1983: 16.4.21) mentions that they have springs which they use both for domestic purposes and for watering their agricultural plots.
5. The great majority of the pottery was picked up near the foundations of the older dwellings. The ceramic analyses were carried out predominantly by Sarah Wenner during the 2013 and 2014 Udhruh campaigns. For further reading see Wenner, 2015.
6. For this the TopCon Total Stations of the Al-Hussein Bin Talal University were used and a Leica P30 Scan-station was brought from the Netherlands.
7. Parts of these will be carried out at the Technical University of Delft (Water Resources Management, Civil Engineering and Civil Sciences) under the supervision of Maurits Ertsen.
8. Hippocrates (1923, VIII). Hippocrates warns here of the resulting degradation in taste, which might be made even worse when this water was blended with water from other sources. This view of the blending of water from different origins remained current in Roman times, as can be read in Vitruvius (1934, VIII.1–3).
9. When working in agriculture in Zambia and Zimbabwe in the 1990s I noticed people who took simple but effective measures to prevent evaporation from dams and reservoirs by making coverings of wicker, banana leaves and sturdy grasses (e.g. *Pennisetum purpureum*).
10. For the ground-penetrating radar (GPR) we have a collaboration with the Technical University of Delft, and an FM256 dual-Fluxgate Gradiometer is owned by the Al-Hussein Bin Talal University.
11. Further technical analyses of these mortars would make an interesting addition, for which we are thinking of chemical analysis, X-ray fluorescence and diffraction, compression testing and micro-morphological research. Most of this can be executed at our Laboratory for Material Culture Studies in the Faculty of Archaeology at Leiden University.
12. This was a result from both recent surveys and older ones carried out in the early 2000s (Abudanh, 2006: 73).
13. As was carried out by Erica van Hees of the archaeo/palaeobotany laboratory of the Faculty of Archaeology, Leiden University.
14. These tests were carried out and analysed by André van Leeuwen and Marcel Hoosbeek at the Department of Soil Quality, Wageningen University.
15. This was executed by a student of Civil Engineering and Geosciences at the Technical University Delft, under the supervision of Maurits Ertsen.

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Water Societies and Technologies from the Past and Present

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UCLPRESS

First published in 2018 by
UCL Press
University College London
Gower Street
London WC1E 6BT

Available to download free: www.ucl.ac.uk/ucl-press

A CIP catalogue record for this book is available from The British Library.

ISBN: 978-1-911576-71-6 (Hbk.)
ISBN: 978-1-911576-70-9 (Pbk.)
ISBN: 978-1-911576-69-3 (PDF)
ISBN: 978-1-911576-72-3 (epub)
ISBN: 978-1-911576-73-0 (mobi)
ISBN: 978-1-911576-74-7 (html)
DOI: https://doi.org/10.14324/111.978191157693

Preface

Inspiration for this volume came from extensive fieldwork in Asia conducted by us, the editors, as well as discussions about establishing a new course on ‘Rivers and Civilisations’. However, rather than focusing on a course, we thought it would be a good idea to establish a small conference on water-related issues that covered a variety of settings and periods, to see what commonalities might be determined across time. A benefit of archaeology is that it provides a long-term perspective on the use of critical resources such as water. We thought a conference that looked at different cases, applying archaeological methods focused on water, while also inviting noted scholars of current issues relating to water, could provide a longer view of the major issues debated, such as water sustainability, technology and management.

In choosing who to invite to participate, our intention was to incorporate cutting-edge research conducted by various scholars and see how their research addresses the main areas of focus on the topic of water. The main issues we cover are how water relates to societies across time, the technologies of water, and how we can understand water-related issues across time through models (conceptual and quantitative) of water use and management. By the nature of these topics, the scholars’ work had to be interdisciplinary, and often collaborative.

The intention is still to gather momentum for an interdisciplinary teaching initiative on water that aims to provide a coherent overview of how water technologies and societies have co-evolved. The concept of sustainability, we thought, also required investigation, since past and even modern cases have begun to challenge it. A comparative conference could test these ideas and indicate the feasibility of theme-based approaches that are not wedded to disciplines such as archaeology but look at a critical resource across time.

Initial invitations were sent to potential participants, and we received very positive feedback from a variety of scholars in China, the United States, the UK and elsewhere in Europe. This helped us put forward a strong application for funding, which was ultimately accepted. We are therefore grateful to the Institute of Archaeology and the Institute of Advanced Studies at UCL for their generosity in funding the conference, which was entitled ‘Comparative Water Technologies and Management: Pathways to Social Complexity and Environmental Change’.

This conference proved successful; it focused on the main water-related issues outlined above. Particularly stimulating was the post-presentation group discussion in a seminar room, which not only addressed the achievements of the conference but helped develop the foundations of this volume. We had the opportunity to share, in a relaxed manner, common concerns, our vision – both humble and grand – of future research directions, and anecdotes about fieldwork and interdisciplinary collaborations. Perhaps what was telling was that, outside the building on Gower Street where the conference was held, anti-austerity protestors were marching. We gave sandwiches, which could be considered delicious by UK conference standards, to the upbeat protestors.

Ultimately, we wanted our ideas to be heard and shared more widely, hence this edited open access volume you are reading. We have not made this book simply a proceedings volume. Rather, authors were asked to refine their work to focus on the key takeaway themes that were developed in the conference, so that a larger, more coherent picture could be developed of the long-term use of water and of how different case studies could inform us about how societies have integrated water resources across time.

We thank our contributors for their quick response to emails and for producing their work to a tight production schedule. We are also grateful to UCL Press for making this book happen. In a radically changing publication climate, UCL Press has become a pioneer by making all its publications open access. We are confident that this volume will be a small and stimulating start to a long academic journey that puts water, one of our most critical resources, at the centre of an interdisciplinary and long-term understanding of how this critical resource has been used across time, and the lessons this use has for us today.

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