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The Hydraulic Infrastructure of Petra: A Model For Water Strategies in Arid Land

Introduction

The starting point for an overall study research investigating the hydraulic infrastructure of ancient Petra was the excavation and restoration project in the as-Sīq (Belwald *et al.* 2003), which provided the first clear and undeniable archaeological evidence for the construction, the functioning and dating of the system. Based on these results, the author began a survey of the entire Petra area in 1997 in order to document all the visible remains of other hydraulic systems. The evaluation of the recorded elements led to a preliminary model of Petra's hydraulic infrastructure in antiquity. Furthermore a first relative chronology could be established, showing how the entire system was developed over the centuries, how it declined and finally collapsed. For each single element of the system its function in the entire network and its technical and constructive characteristics could be determined.

The Water Supply in the Early Phases of the City Development

It was already well known from written sources[1] that at the beginning of their settlement in Petra the Nabataeans maintained their traditional Bedouin way of living in tents. The Swiss-Liechtenstein Excavations at az-Zanṭūr was able to show these ancient written sources to be correct when they discovered the battered dung layers of this tent occupation and even some of the holes from the posts supporting the tarpaulins (Stucky *et al.* 1996) How the water supply for this tent settlement functioned is still unknown. Again known from written sources[2] and now confirmed by various excavations[3]: at the beginning of the first century BC Petra began to develop as a stone built city. This still modest city got its water supply from cisterns collecting runoff water from the roofs and from the surrounding areas. One of these early cisterns was excavated by the team of Basel University below the mansion at az-Zanṭūr IV. It dates to the first half of the first century BC and was then built over by the foundations of a construction from the very beginning of the first century AD (Kolb 2001). In the middle of the first century BC the developing city underwent a strict urban planning and was completely remodeled as a Hellenistic capital. For this new Hellenistic urban centre a completely new water supply system had to be built, providing the growing population with spring water and feeding the city's outstanding monuments.

The First Spring Water Aqueduct

The excavations in the as-Sīq revealed sections of an underground gravity flow channel which followed the surface of the trampling path before the construction of the paved road. This channel was covered over its entire length and crossed wider faults on dams or even arched bridges (Bellwald 2003). In summer 2004 the joint excavation of Graf, Schmid and Bedal unearthed further sections of the same channel in the vicinity of the Temenos gate proving that this first aqueduct reached the city centre[4]. Due to the modern building activity

[1] Description of the military campaign of Antigonos Monophtalmos against the Nabataeans in 311BC, written by Hieronymos of Cardia and recorded by Diodorus Siculus (90-21BC) in Bibliotheca Historia XIX, 94-100.

[2] Description of the Nabataeans and Petra by Artemidor of Ephesos, recorded by Strabo (63BC – 24AD) in Geography XVI iv. 26.

[3] Parr, P.J., Excavations at Petra 1958-59, Palestine Exploration Quarterly 92, 1960; Stucky, R., 1996; Augé, C. and others, The Excavations of IFAPO in the Qasr al-Bint Area, Editions Recherches sur les Civilisations, forthcoming; Graf, D., Schmid, S., Bedal, L.A., The Hellenistic Petra Project, forthcoming.

[4] Hellenistic Petra Project, forthcoming.

in the town of Wādī Mūsā, no remains of this first channel have yet been discovered between Bāb as-Sīq area and the springs to the East of the city, thus the original feeder of the aqueduct cannot be determined. However, based on the wide cross section of the channel it must have been a spring with a great capacity, and therefore it was most probably 'Ayn Mūsā.

The sections of this first gravity flow channel excavated in the as-Sīq have shown that the first aqueduct must have been destroyed by a flash flood in the middle of the first century BC (Bellwald 2003). The constructive characteristics of the first spring water channel, as revealed by the excavated sections in the as-Sīq and near the Temenos Gate and by the still visible remains in the Bāb as-Sīq area, clearly show that this was built as a completely hidden, underground construction. Such buried aqueducts were common in the Greek motherland since the archaic period and were widely adopted in the Hellenistic cities in Asia Minor (Garbrecht 2001). The same model was adopted for the first aqueducts built in Rome, as may be shown by the Aqua Marcia[5].

The Khubtha North Aqueduct

The first spring water aqueduct which was obviously built for the developing Hellenistic urban centre was the Khubtha North aqueduct (FIG. 1). As the older underground channel it had a wide cross section and hence must have used the 'Ayn Mūsā spring. It immediately replaced the destroyed oldest channel in the as-Sīq and was the first aqueduct to be built as a completely visible structure above ground, with imposing arched bridges up to a span of more than 13m (FIG. 2). Contrary to older studies (Gunsam 1970) the Khubtha North channel was fully covered and had no deviation between the spring and the end reservoir besides the Palace tomb. A sequence of 3 water basins in front of the end reservoir assured the supply of spring water to the public. Before it reached Wādī Shi'ab Qays, the Khubtha North aqueduct supplied a huge storage basin in Ramla, providing the mills and the pottery work shops of the area with water (FIG. 1) ('Amr and Momani 1999). The arched bridges of the Khubtha North aqueduct collapsed in the earthquake of 363AD and were never rebuilt; hence the entire aqueduct went out-of-use after this date.

The as-Sīq Aqueduct

The first element of the spring water supply system in the as-Sīq to be built was the terracotta pipeline, installed in the third quarter of the first century BC (Bellwald 2003) (FIG. 3). It had its end reservoir at the eastern end of the colonnaded street, where a splendid Nymphaeum served as a public fountain (FIG. 1). In the Roman period, under the Severian emperors, the northern Nymphaeum was added. The terracotta pipeline in the as-Sīq was, due to its gradient, under pressure, but the pressure was not used to reach areas located on a higher level than the conduit of the pipe. In the second century AD a second branch was added to the original pipe, with its partition chamber below Khubtha fault 6 (FIG. 5). This secondary pipe did not make use of the high internal pressure, as may be proved by its conduit high up in the cliff of the outer as-Sīq. This later, additional branch supplied an area opposite the theatre which was located on a much higher level than the end reservoir of the original pipeline (FIG. 1). To reach it the new branch was built with a very flat gradient that required a conduit high up along the cliff of the outer as-Sīq. This type of construction is another proof that no use was made of internal pressure in the pipeline. During the third century AD there was a risk of damage from increased internal pressure caused by the lime built up inside the pipe. In order to prevent the entire conduit from being destroyed, the top of the pipe was opened, after which it further functioned only as a gravity flow channel (FIG. 3). In the earthquake of 363AD the pipe was finally destroyed and was not repaired again.

The second element of the water supply system in the as-Sīq was the gravity flow channel following its southern cliff (FIG. 4). It was built in the mid first century AD and originally only supplied the Khazna Plaza with drinking water (Bellwald 2003). Partially destroyed in the earthquake of 363AD, it was then repaired and extended into the city centre[6]. After the earthquake the repair was done in a rather sloppy manner and the channel was no longer covered. It seems that the channel in the as-Sīq still functioned during the late period of Petra's existence until the early eighth century AD. Both as-Sīq aqueducts used the water from 'Ayn Mūsā.

[5] Fahlbusch, H., 1981, Die Wasserversorgung des Antiken Rom, Mainz.

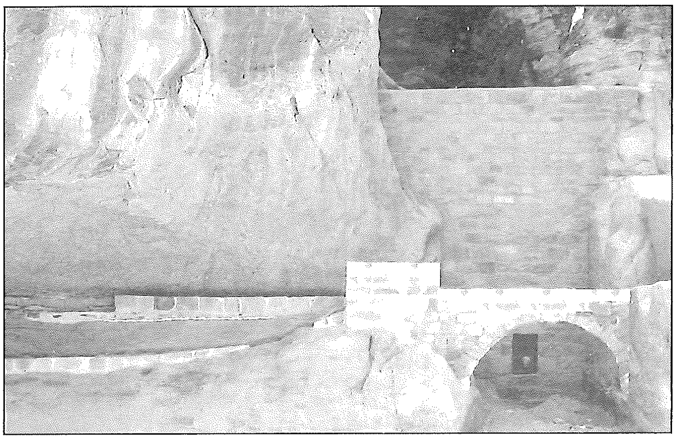
[6] Proved by a sounding in the outer Sīq, executed by the Department of Antiquities in 1998, but still unpublished.

1. The water supply system of Petra after its completion at the end of the first century AD:
Spring Water Aqueducts:
As-Sīq Aqueduct
Terracotta pipeline, 3rd quarter of the first century BC
Gravity flow channel, mid first century AD.
1a. End reservoir of the terracotta pipeline with public fountain.
1b. Branch added to the terracotta pipeline, second century AD, end reservoir opposite the theatre.
Khubtha North Aqueduct
Gravity flow channel, mid century BC
2a. Storage basin at Ramla for the supply of the mills and pottery kilns at az-Zurraba.
2b. Preserved arched aqueduct at Shi'ab Qays.
2c. Collapsed arched aqueduct at Wādī Zarnuq.
2d. End reservoir and public fountain to the North of the Palace tomb.
'Ayn Brāq Aqueduct
3a. Castellum Divisorum.
3b. End reservoir at az-Zanṭūr.
3c. End reservoir flanking the Paradeisos.
'Ayn Dibdba Aqueduct
4a. End reservoir opposite Qaṣr al-Bint
'Ayn Abū 'Ullayqa Aqueduct
Runoff Water Collection Systems:
A. Wādī Farasa East
B. Wādī Farasa West
C. Wādī an-Nimr
D. Jabal al-Mu'ayṣra East
E. Jabal al-Mu'ayṣra West
F. ath-Thughra
G. ad-Dayr Plateau
H. Qaṭṭār ad-Dayr
I. Wādī al-Maṭāḥa
K. Mughur an-Naṣārā
Aerial Photo Royal Geographic Centre, Amman 2000. Display of water supply system U. Bellwald.

2. Khubtha North aqueduct, the arched bridge crossing Wādī Shi'ab Qays, built mid first century BC. The arch has a span of 7m.
Photo and computer-simulation U. Bellwald.

3. The water pipe of the as-Sīq aqueduct, built in the 3rd quarter of the first century BC.
Photo U. Bellwald.

4. The gravity flow channel of the as-Sīq aqueduct, built mid first century AD. The section shown includes a settling tank (top right).
Photo U. Bellwald.



5. The partition chamber at the lower end of the arched bridge crossing Khubtha Fault 6, added to the aqueduct during the second century AD.
Photo and computer-simulation of the original aspect U. Bellwald.

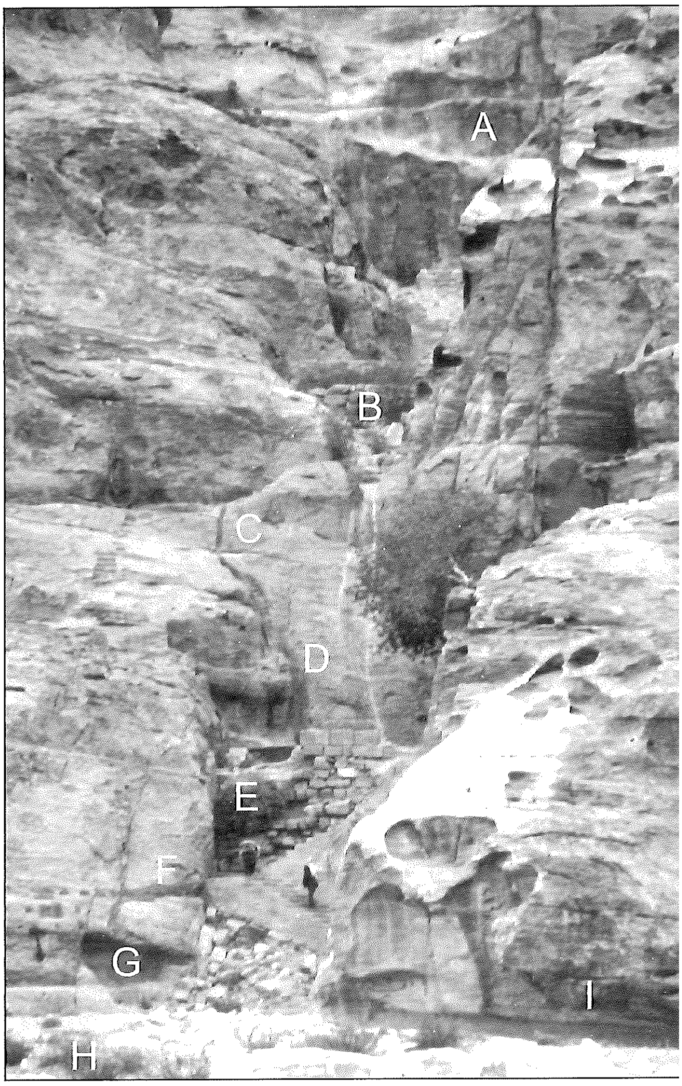
The 'Ayn Brāq Aqueduct

The 'Ayn Brāq aqueduct provided the Southwestern quarter of the city with drinking water (FIG.

1). It was a double aqueduct, consisting of a terracotta pipeline and a gravity flow channel. Due to the steep and rocky areas between the spring and the city the conduits of the pipe and the channel are not parallel at all; mostly they have their own individual line. To prevent the pipeline from being destroyed by internal pressure due to extreme gradients, decompression tanks were built below steep stretches.

The 'Ayn Brāq aqueduct has two end reservoirs, one on top of az-Zanṭūr hill, and the other flanking the pool complex beside the Great Temple (FIG. 1). The partition chamber is located between the cliff of Jabal al-Madhbaḥ and az-Zanṭūr (FIG. 6). As there is a difference in level of about 16m between the aqueduct's entry into the city area and the end reservoir on top of az-Zanṭūr the pipeline had to use its internal pressure to transport the water. Coı trary to earlier studies (Lindner and Hübl 1997) tl 'Ayn Brāq aqueduct had no forks for the supply ‹ the suburban areas in the plain of al-Qanṭara and : Wādī Farasa, all hydraulic installations there we: based on runoff water collection (FIG. 7). The 'A) Brāq aqueduct developed the model of the as-S: pipeline to perfection; it is characterized by ou

6. 'Ayn Brāq aqueduct, partition chamber about 100m below the descent into the city area. The right branch leads up to the public reservoirs on top of az-Zanṭūr, the left one down to the reservoirs flanking the Paradeisos.
Photo U. Bellwald.



7. The terraces above and below the lion fountain in Wā Farasa East:
A. 'Ayn Brāq Aqueduct with no deviation to the lower tε races.
B. Dam for the water supply of the lion fountain.
C. Supply channel of the lion fountain.
D. Lion fountain.
E. Dam of the pool in front of the lion fountain.
F. Overflow channel from the pool in front of the lion fou tain to the lower pool.
G. Fountain supplying the lower pool.
H. Lower pool.
I. Overflow channel from the lower pool to the cistern belo the great staircase, leading to the terrace of the garden tı clinium.
Photo U. Bellwald.

standing constructions, mostly built in beautiful embossed ashlar blocks. Its arched bridges outside the city must have been of such impressing appearance that their ruins still survive in the name of the area: Al-Qanṭara means arch! Based on its construction, the aqueduct may be dated to the end of the first century BC, dating which is confirmed by the results of the excavations at the pool complex beside the Great Temple (Bedal 2004). As the Swiss-Liechtenstein excavation at az-Zanṭūr IV has proved, the mansion situated on a promontory at the southern slope of the hill had direct water supply from the end reservoir on the hilltop (Kolb 2002). Therefore, just as at Pergamon, Priene, Ephesos and Pompeii, at least the most important private houses of the city had direct drinking water supply. As with most of the other aqueducts, the 'Ayn Brāq conduit was destroyed by the earthquake of 363AD and never rebuilt.

The 'Ayn Abū 'Ullayqa Aqueduct

The 'Ayn Abū 'Ullayqa aqueduct connects the spring in the lower Wādī Turkmāniyya with the sacred area of Petra, the Temenos of Qaṣr al-Bint (FIG. 1). Unfortunately the section in the city area itself has been completely washed away by flashfloods. The 'Ayn Abū 'Ullayqa aqueduct follows the model of the 'Ayn Brāq aqueduct: it consists of a terracotta pipeline and a gravity flow channel and shows exactly the same type of construction with beautiful embossed ashlar blocks and evidently dates to the same period, i. e. towards the end of the first century BC. Due to the low gradient between the spring and the end of the city basin, the channel and the pipeline of the 'Ayn Abū 'Ullayqa aqueduct follow parallel conduits. No statements may be made in regard to the destruction of this aqueduct.

The 'Ayn Dibdba Aqueduct

The 'Ayn Dibdba aqueduct brings the water from the spring above the actual village of the Amarin Bedouins into the city basin. It supplied the northwestern quarter of the city with drinking water (FIG. 1). With a terracotta pipeline, a gravity flow channel and decompression basins below steep slopes, the 'Ayn Dibdba aqueduct technically follows the model of the 'Ayn Brāq aqueduct. In its construction however it differs remarkably from the outstanding 'Ayn Brāq aqueduct, its built sections consisting of masonry from collected broken stones. From its end reservoirs only the one opposite Qaṣr al-Bint is known for the moment, but evidently there must have been prior ones below the northern ridge of the city area (FIG. 1). It must be supposed that the 'Ayn Dibdba aqueduct was the last of the five spring water aqueducts to be built; it may be dated to the late first century AD. As with most of the other aqueducts, it was destroyed by the 363AD earthquake, and was not rebuilt.

The Later Water Supply of the City Basin

As most of the splendid aqueducts of Hellenistic Petra were destroyed in the earthquake of 363AD and not rebuilt, other water systems had to be installed for assuring the supply of the population. From the aqueducts only the gravity flow channel in the as-Sīq was repaired and prolonged into the city centre. A section of this new branch of the channel has been excavated in front of a tomb in the outer as-Sīq[7] . This section of the channel is clearly related to the Byzantine level of the paved street, which was several meters above the Nabataean pavement. This channel was no more covered, therefore inside a thick layer of lime and leaves and small branches built up, slowly reducing its capacity (Bellwald 2003). For additional water supply, the tremendously reduced population of the declining city returned to runoff water collection systems, as may be shown by the cistern in the courtyard in front of the Petra Church (Fiema 2001).

In Conclusion

At its final stage, the spring water supply system of Petra covered the entire area of the city basin, bringing spring water from the east, south and North into the city. The location of the end reservoirs shows that all four quarters of the city had their own aqueduct (FIG. 1). Normally public fountains provided the inhabitants of Petra with drinking water, but as may be proved by the mansion at az-Zanṭūr, at least some of the houses were directly connected with the public reservoirs. This research has clearly shown that all spring water aqueducts were entirely closed and did not collect runoff water along the cliffs, as has been suggested before (Gunsam 1970; Lindner 1997) (FIG. 7). Furthermore all 5 aque-

[7] Executed by the Department of Antiquities in 1998, but still unpublished.

ducts had no deviations into areas outside the city basin. The only hydraulic installations supplied by one of the spring water aqueducts outside the city basin discovered to-date are the four drinking basins excavated in the as-Sīq (Bellwald 2003).

The Flash Flood Prevention System

The excavations in the as-Sīq revealed a highly sophisticated flash flood prevention system, consisting of a series of dams and stilling basins built to protect the hydraulic constructions from being destroyed by the winter water masses (Bellwald 2003). The survey has shown that the other four aqueducts were protected by similar constructions. Furthermore the survey proved that all wadis and faults leading into the city area were included in the flash flood prevention system. At each outlet of such wadis and faults retention dams were built in order to control the outflow of water (FIG. 8). The most spectacular remains of such dams are located at the outlet of Wādī Umm Ṣayḥūn into Wādī al-Maṭāḥa, at the outlet of Wādī al-Jarra into Khazna Plaza[8] (FIG. 9) and in Wādī Farasa East (FIG. 8). Ruins of dams on Khubtha hill, on the plain of al-Qanṭara, al-Madrass and al-Jilf bear witness that part of the water from winter rainfalls was already retained on the natural terraces high above the city area (FIG. 8).

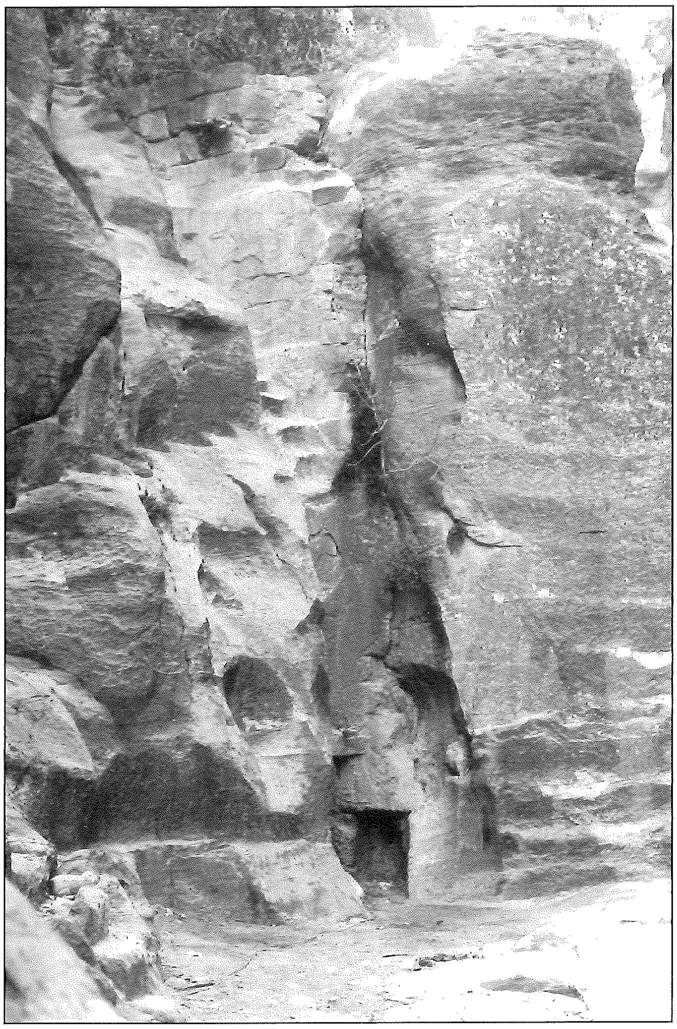
The Runoff Water Collection Systems

Areas around the city, which were not constantly inhabited, were not supplied by the spring water aqueducts, but had their local, independent and individual runoff water collection systems. All these various systems have some common characteristics: channels at the bottom of cliffs which collect the runoff water and direct it into collection basins. The function of these basins was to tame the tormented water and let silt settle down. In a sequence of following settling tanks the still dirty water was further cleaned and filtered. The end station was a fully covered cistern with an internal staircase for maintenance and an opening for drawing water (FIG. 10). This opening was normally covered by a metal lid, cautiously embedded into the covering slabs. Most of these cisterns were carved into the bedrock and their covering slabs were supported by segmental arches. The complete exclusion of daylight prevented the water in the cisterns from being polluted by bacteria and algae. In special locations diversion dams had to be built on top of the system in order to dam the water up to the level of the channels leading to the collection basin. The most spectacular of these was built in outer Wādī Farasa West (FIG. 1).

8. The Flash Flood Prevention System:
A. Retention basin, diversion dam and bridge in front of the as-Sīq entrance.
B. Diversion tunnel from Wādī Mūsā into Sīq al-Mudhlim.
C. Retention Dam in Sīq al-Mudhlim.
D. Retention dams in Wādī Maṭāḥa.
E. Retention walls and dam in Wādī Umm Ṣayḥūn.
F. Retention dams on top of Jabal al-Khubtha.
G. Retention dams on the natural, intermediate terraces of Wādī al-Madrass and Wādī al-Jilf.
H. Retention dams on the natural, intermediate terraces of Wādī al-Qanṭara.
I. Retention dams at the outlet of Wādī al-Jarra into Khazna Plaza.
K. Retention dam in Wādī Maḥfūr.
L. Retention dam in outer Wādī Farasa East.
Aerial Photo Royal Geographic Centre, Amman 2000. Display of flas flood prevention system U. Bellwald.

The runoff water supply systems generally provided necropolis and sacred areas with water. However, new excavations in Wādī Farasa East have shown that some of the areas close to the city were

[8] Wādī al-Jarra enters Khazna Plaza in two arms. Whereas the dam at the bottom of the wider arm collapsed in the earthquake of 363AD, the two superimposed dams of the narrower arm are completely preserved.



9. Fully preserved retention dam at the outlet of the narrower, eastern branch of Wādī al-Jarra into Khazna Plaza. The niche at the bottom of the dam contains the valve which assured a continuous outflow of water.
Photo U. Bellwald.

inhabited too (Schmid and Studer 2003). In addition the International Wādī Farasa Project has uncovered archaeological evidence for a precise dating of the runoff water collection system into the beginning of the first century AD (FIG. 7). Another such a suburb existed most probably at ath-Thughra, a location close to the necropolis of the snake monument (FIG. 1). Other runoff water supply systems were built along the caravan routes, providing men and animals with water. Such systems are located along the routes into Wādī Ṣabrā and the one bypassing Jabal Hārūn, leading to the Negev[9] (FIG. 1). At least one runoff water collection system is known at the outlet of Sīq al-Ba'ja, which was built for the irrigation of fields, allowing a certain agricultural production on the higher banks flanking the wadi bed (Bienert *et al.* 2000).

The Nabataean's Contribution to the Development of Hydraulic Systems and Constructions

The precise dating results of the excavations in the as-Sīq have clearly shown that the terracotta pipes with which the aqueduct was built are the oldest ones found to be manufactured on the potter's wheel (Bellwald 2003). It is obvious, therefore, that the Nabataeans, very sophisticated potters, adopted the technology which they had developed for the production of fine ware bowls for producing industrial terracotta ware such as water pipes. The pipes excavated in the as-Sīq, manufactured on the wheel, are not longer than a yard and have a ribbed/rippled inner surface which is due to the movements of the potter's fingers. This ribbed/rippled inner structure,

10. General view onto one of the runoff water collection systems at the eastern slope of eastern Jabal al-Mu'ayṣra, showing a perfect model for such a system.
Photo and display of runoff water collection system U. Bellwald.

[9] Lindner, M. and others, 2004, Beyond Petra, 30 Years of Fascination and Research, Rahden.

first only a consequence of the production on the wheel was then detected to be of great influence for a better flow of water, as it led air bubbles in the water to the top of the pipes. The pipes produced on the wheel were much thinner than the pipes produced from flat tiles around a cylindrical mould and therefore of tremendously reduced weight, a fact that increased their applicability. Due to the very thin walls of the pipes the Nabataeans seemed to be the first ever to have their pipelines completely embedded in lime mortar.

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