
The Water Supply and Distribution System of the Nabataean City of Petra (Jordan), 300 BC–AD 300

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The water supply and distribution system of the Nabataean city of Petra in southwestern Jordan has been explored and mapped. Analysis of the system indicates exploitation of all possible water resources using management techniques that balance reservoir storage capacity with continuous flow pipeline systems to maintain a constant water supply throughout the year. Nabataean Petra was founded c. 300 BC; urban development progressed with later Roman administration of the city starting at AD 106; Byzantine occupation continued to the seventh century AD. Trade networks that extended throughout much of the ancient Near East and Mediterranean world intersected at Petra, and brought not only strategic and economic prominence, but also impetus to develop water resources fully to sustain demands of increasing population and city elaboration. City development was influenced by artistic, cultural and technological borrowings from Seleucid, Syro-Phoenician, Greek and Roman civilizations; the Petra water-distribution system included hydraulic technologies derived from these contacts as well as original technical innovations that helped to maintain the high living standard of city dwellers throughout the centuries. Analysis of the Nabataean water network indicates design criteria that promote stable flows and use sequential particle-settling basins to purify potable water supplies. They also promote open channel flows within piping at critical (maximum) flow rates that avoid leakage associated with pressurized systems and have the design function to match the spring supply rate to the maximum carrying capacity of a pipeline. This demonstration of engineering capability indicates a high degree of cognitive skill in solving complex hydraulic problems to ensure a stable water supply and may be posited as a key reason behind the many centuries of flourishing city life.

Positioned between Egyptian, Babylonian and Assyrian empires, many influences dominated the formative Nabataean cultural landscape over time. The sacred spring created by Moses, as described in Exodus accounts, has been equated with the Ain Mousa spring outside Petra although controversy exists as to its location (and historical accuracy) and sites in Sinai must also be considered. Biblical and Koranic references to the Petra area document use of water channels and springs by the inhabitants to maintain agriculture and settlements. Assyrian texts ascribed to the Sargonic era (715 BC) mention tent cities in this area. The earliest proto-Nabataean period (sixth century BC) began when

Edomite agriculturalists assimilated nomadic tribal groups familiar with caravan-based trade activities. Although the origins of the Nabataeans remain controversial (Taylor 2001; Guzzo & Schneider 2002; Gleuck 1959; 1965), their final consolidation in areas around Petra in the early third century BC is evident from the archaeological record. Following conquest by Alexander and the later division of his empire, conflicts arose between the Nabataeans, Antigonos of Macedonia and Ptolemaic forces for control of the lucrative trade routes passing through Petra. With the decline of Seleucid and Egyptian influences, a Nabataean state emerged in 64 BC. Roman intervention began when

Scaurus, an envoy of Pompey, sided with Nabataea's enemies to defeat Aretas III in battle (64 BC). Rome declared the province of Syria under its control, and Nabataean-controlled areas were subject to Roman invasions under Scaurus (62 BC) and Gabinius (55 BC). Despite the tumultuous political climate, Nabataean political wisdom prevailed to maintain the establishment of an important trading empire with Petra as the main administrative, commercial and religious centre. A series of Nabataean kings (Aretas I, c. 168 BC; Aretas II, 120/110–96 BC; Obodas I, 96–85 BC; Rabbel I, 85/84 BC; Aretas III, 84–61 BC; Obodas II, 62–58 BC) presided over the expansion of commerce and urbanization at Petra, driving the city's increasing water needs. Nabataean acquiescence in the inevitability of Roman dominance, and the commercial advantages of trade across territories consolidated under Roman rule, outweighed the advantages of autonomy. The city experienced Roman control under Tiberias, Caligula, Claudius, Vespasian and Hadrian, with administrative consolidation and territorial status change characterizing Roman dominance. Allied to Rome, Nabataeans, under King Malichus, were participants in suppressing the Jewish revolt in AD 67 (Josephus 1960). Rabbel II (AD 70) then ushered in independence as a Roman ally that permitted Petra to continue its trade-based prosperity. Petra was formally annexed into the Roman Empire in AD 106 under Trajan. Throughout this period, caravan trade from Arabia, Africa and the East, with Petra as a key intersection node, sustained the city's wealth and supported the construction of commercial, ceremonial, administrative, manufacturing and water-supply structures commensurate with the city's wealth and status as an emporium city. Under Roman governance of Syria, the Nabataeans enjoyed relative independence, perhaps on account of tax and tribute revenue to Rome. Wealth generated by trade and taxes on caravans to Cairo, Gaza, Damascus, Palmyra, Jauf, Median, Madain-Salih and Eastern locales, came finally under Roman dominance. The gradual shift to sea trade (Taylor 2001) led to the decline of Petra's status as an overland trade centre, with Palmyra now replacing Petra for overland caravan traffic from Silk Road destinations. Following Arab occupation after the collapse of the Byzantine Empire, the city faded from view until European rediscovery in the nineteenth century. Further historical accounts (Taylor 2001; Guzzo & Schneider 2002; Gleuck 1959; 1965; Hammond 1973; Levy 1999; Auge & Denzer 2000; Bowersock 1983; Bourbon 1999; Browning 1982) detail the many cultural and developmental influences the city experienced over many centuries of existence.

Historical background of Petra's water-management strategies

It is clear that many exterior cultural, political and technological influences colour the history of Petra. Consequently, the water-supply system may be expected to reflect borrowings from the best civil engineering practices of neighbouring civilizations and innovations derived from demands of the complex topography and limited water resource base of the area. Innovations derived from direct experience of desert water-conservation measures are also to be expected given the nomadic background of the Nabataeans. Egyptian, Mesopotamian, Minoan and Greek civilizations all utilized piping systems for water supply and wastewater drainage. For example, the Temple at Knossos (Crete) at 2100 BC incorporated systems of conical, interlocking, terracotta piping elements in the main palace water system; later, the Hellenic Temple of Artemis (Turkey) dating to 800 BC incorporated strings of socketed, mortared, terracotta pipes as well as lead-pipe segments joined by stone connectors to transport water from nearby springs. The Hanging Gardens of Babylon, during the reign of Nebuchadnezzar (605–562 BC), incorporated a high-level reservoir from which water was delivered to terraces and fountains through hydrostatically pressurized terracotta pipelines. Egyptian copper and brass piping systems associated with 5th Dynasty Temples at Abusir form part of temple drainage systems to the Nile. Athens in the 6–7th century BC and Olynthos had systems of interlocking terracotta pipes sealed by mortar, while the Ionian city of Priene (Turkey) in the third century BC had elaborate terracotta piping networks complete with filtration systems to purify water prior to distribution to city fountains (Ortloff & Crouch 1998). In concept, many of these systems are quite similar to those observed at Petra, indicating some use of previously-established technologies from surrounding societies. New learning gained through years of trade activity to many corners of the ancient world would have provided yet further sources of hydraulic knowledge. An early example of the Nabataean ability to learn from prior technologies is the 27-km-long Humeima canal from springs in the Sharma Mountains to a Wadi Rum outpost, attributed to Obodas I (96–86 BC) (Taylor 2001). This subterranean canal indicates that low-angle surveying technology was already understood — perhaps a borrowing from Greek and Roman geometric traditions (Cohen & Drabkin 1966; Lewis 2001). Combined with hydraulics knowledge from earlier sources this canal demonstrated it was possible to design a canal

that matched spring output to canal carrying capacity. These examples indicate that while knowledge of piping systems was widespread in archaic times, initial use was mostly associated with elite civil and temple structures. Canal-building technology, on the other hand, was widespread throughout the ancient Middle East and primarily used for agricultural purposes. Gradually it was extended to city-wide piping networks — an idea reaching maximum extent in later Roman cities where branch piping fed individual living quarters. An early technology base, utilizing pipeline and canal systems, existed well before Nabataean times and was surely available to aid in the planning and development of Petra's water system. Contact with many cities benefiting from the Roman revival of water-supply systems (Ortloff & Crouch 2001; Crouch 1993) undoubtedly accelerated knowledge of city-wide water systems that could be used at Petra. The limited water resources (springs and rainfall capture) and complex mountainous terrain of the Petra area, however, meant that old ideas required new thinking to produce a distributed water system that provided a constant, year-round water supply, given variations of seasonal rainfall and spring flow. The story to be told here relates to the archaeological record of Nabataean solutions to the water-supply demands of a large urban population. As will be demonstrated, modern computer simulation of hydraulic phenomena within ancient piping systems can reveal further knowledge underlying Nabataean pipeline design and water management and reveal subtle aspects of their contribution to the hydraulic sciences.

Description of the Petra water supply and distribution system

Figure 1 shows details of the supply and distribution system leading water to the urban core of Petra. Numbered locations (in round brackets throughout the text) denote major buildings, temples and site features as listed in the key to Figure 1. Also shown are major dams (d), cisterns (c), water-distribution tanks (T) and springs (S). The superimposed grid system (A,B,C;1,2,3) serves to define an area coordinate system composed of 1 km² grid boxes to permit approximate location of various features mentioned in this discussion.

The urban core of Petra lies in a valley surrounded by high mountainous terrain (Fig. 1). Seasonal rainfall runoff passes into the valley through many canyon streambeds (wadis) and drains out primarily through the Wadi Siyagh (A;2). Early phases of urban Petra relied upon open channel water delivery from the

Ain Mousa spring outside the city along a direct path through the Siq (Fig. 1). The water channel traversed the entire length of the city before exiting into Wadi Siyagh. Placement of this system required diversion of the intermittent Wadi Mousa River, that (previously) passed through the Siq, by means of dam and tunnel construction (8). Later phases of urbanization reveal an integrated approach to water-system construction and management, demonstrated by new features such as surface cisterns to capture rainfall runoff; deep underground cisterns; multiple pipeline systems and storage reservoirs; floodwater control through diversion dams and tunnels; supply system redundancy to ensure water delivery from multiple spring and reservoir sources; and pipeline sand particle filtration and removal basins. These later modifications largely reflect the need to bring potable water into the city core at higher elevations to serve hillside occupation zones above the valley floor. Since the open channel in the Siq ran along a path at about the same height as the lowest Wadi Mousa riverbed, its ability to supply water to outlying urban zones above the riverbed was limited. The later changes of the Petra water system demonstrate continual evolution of the urban water-supply system through time and reflect the application of newly-acquired technologies integrated with indigenous hydraulic innovations to provide for the increasing water needs of the city.

The technical means to capture and store a fraction of the rainfall runoff through dams and cisterns, to build flood-control systems, to build pipelines and channels to deliver water from distant springs, and to manage these interdependent assets to provide a continuous, year-round water supply to the city is crucial to understanding Nabataean contributions to hydraulic science. While water storage was a partial key to the city's survival, a number of springs internal and external to the city (Fig. 1: Ain Mousa, Ain Umm Sar'ab, Ain Braq, Ain Dibdiba, Ain Ammon, al Beidha, Ain Bebdbeh) provided water that was channelled and/or piped to the city. This constituted the main water supply of the urban centre. The complexity and ingenuity of the water-supply systems in Petra was commented upon in antiquity (Strabo 2000) as a remarkable achievement, given the apparent lack of traditional water resources in the area. Strabo's commentary ' . . . and the inside part of the city having springs in abundance, both for domestic purposes and for watering gardens . . . ' reaffirms that springs were a vital part of the city's water resources.

The main Petra water supply originated from the Ain Mousa spring about 7.0 km east of the town of Wadi Mousa (D;1) combined with waters of the

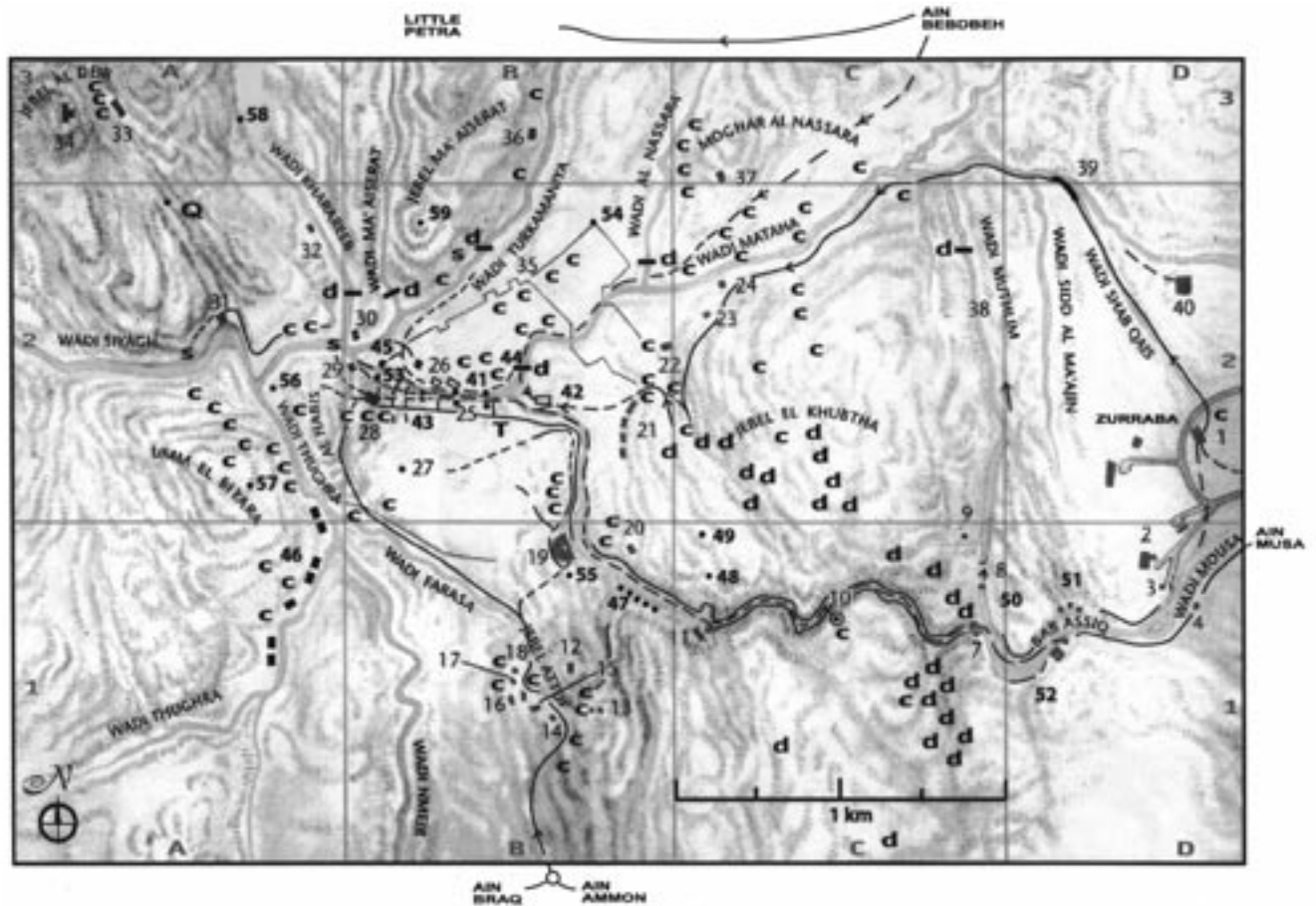


Figure 1. Petra site feature map and water-distribution systems.

Key

d = major dams; c = cisterns; T = water-distribution tanks; S = springs

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| 1. Zurraba Reservoir (al Birka) | 21. Royal Tombs | 41. Byzantine Tower |
| 2. Petra Forum Rest House (Modern) | 22. Sextius Florentinus Tomb | 42. Nymphaeum |
| 3. Park Entrance (Modern) | 23. Carmine Façade | 43. Paradeisos, Market, Hadrian's Gate |
| 4. Hospital (Modern) | 24. House of Dorotheus | 44. Wadi Mataha Dam |
| 5. Dijn Monuments | 25. Colonnade Street (Cardo) | 45. Bridge Abutment |
| 6. Obelisk Tomb and Bab el Siq Triclinium | 26. Temple of the Winged Lions | 46. Wadi Thughra Tombs |
| 7. Entrance Elevated Arch | 27. Pharaoh's Column | 47. Royal Tombs |
| 8. Flood Bypass Tunnel and Dam | 28. Great Temple | 48. Jebel el Khubtha High Place |
| 9. Eagle Monument | 29. Q'asar al Bint | 49. El Hubtar Necropolis |
| 10. Siq | 30. New Museum (Modern) | 50. Block Tombs |
| 11. Treasury (El Khasneh) | 31. Quarry | 51. Royal Tombs |
| 12. High Place | 32. Lion Triclinium | 52. Obelisk Tomb, Snake Monument |
| 13. Dual Obelisks | 33. El Dier | 53. Columbarium Tomb |
| 14. Lion Monument | 34. 468 Monument | 54. Conway Tower |
| 15. Garden Tomb | 35. North City Wall | 55. Tomb Complex |
| 16. Roman Soldier Tomb | 36. Turkamaniya Tomb | 56. Convent Tombs, Crusader Fort |
| 17. Renaissance Tomb | 37. Armor Tomb | 57. Tomb Complex |
| 18. Broken Pediment Tomb | 38. Little Siq | 58. Pilgrim's Spring |
| 19. Theatre | 39. Aqueduct | 59. Jebel Ma'Aiserat High Place |
| 20. Uneishu Tomb | 40. Al Wu'aira Crusader Castle | 60. Snake Monument |

minor Ain Umm Sar'ab spring. This supply still serves the modern town and the associated tourist complex (2), (3) located outside the Siq entrance (10). The Siq

is a 2-km-long, narrow passage through the high mountain range bordering the eastern part of the city core; the steep, canyon-like walls of the Siq provide

nature's preface to the architectural masterpieces ahead in the city centre. In early phases of Nabataean urban development predating the construction of pipeline systems, the main potable water supply derived from an open channel (2 to 2.5 m wide and 1.0 m deep) transporting Ain Mousa spring water through the Siq (C;1). This channel (dashed line, 29 in B;2) extended through the urban core of the city as far as Q'asr al Bint (29) with final drainage into the Wadi Siyagh (A;2). Dam and flood bypass tunnel construction at the Siq entrance, together with infilling and paving of the Siq floor to reduce flooding, has left the channel under the current pavement surface. This pavement is attributed to Nabataean construction under Aretas IV and later Roman paving efforts. The accumulation of flood debris following the city's abandonment for many centuries, in addition to modern attempts to dam and infill the front of the Siq to limit floodwater incursion from Wadi Mousa, have hidden this channel. Recent excavations in front of the Treasury (11 in C;1) to 5 m depth have, however, revealed remnants of this early open channel as well as early tombs cut into mountain walls antedating later Treasury construction. Hexagonal paving slabs and a water basin existed in front of the Treasury location in this early phase (Taylor 2001). While this channel provided water to early phases of the city, the later concentration of urban settlement in areas north and south of Wadi Mousa (B;2) replete with temple, administrative, commercial and civil structures, indicates a transition towards full city status and a hierarchical, stratified and cosmopolitan society involved in trade and commerce. This created demands to increase water supply and distribution to spreading urban settlement areas resulting from population increase. There was also perhaps a desire to match the city's prosperity from trade with appropriate symbols of success. Extensive use of pipelines followed to bring larger amounts of water to areas not reachable by the old, low elevation, open-channel system. Pipeline systems, however, introduced new design complexities that involved knowledge of ways to maintain a stable flow whose maximum (theoretical) flow rate matched (or exceeded) the supply spring flow rate. Flows in poorly-designed pipeline systems are capable of a surprising number of transient, self-destructive hydraulic instabilities (e.g. water hammer, pressure



Figure 2. *The Zurraba (al Birka) reservoir.*

surges, transient wave structure, flow intermittency, internal oscillatory hydraulic jumps, turbulent drag amplification zones, vapour-pocket formation resulting from transition between full and partial flow regions). Thus analysis of Petra's piping systems provides insight into the available technical knowledge that was applied to problem solution and the design principles that were utilized. Additional considerations related to seasonal reservoir and cistern water storage and the routing of pipeline paths to achieve a constant year-round water supply to the city core. This required a bureaucracy to manage the evolving level of complexity. Contour paths had to be surveyed through rugged, mountainous terrain, and choices made of pipeline hydraulic technical parameters (slope, diameter, internal wall roughness, sinuosity, supply head) to match carrying capacity of the pipes to the spring flow rate. These parameters, as extracted from the archaeological record, as well as insights into the management strategy of these assets, help to assess the level of technical achievement of Nabataean engineers.

The reservoir at Zurraba is an example of the later phase technological advances (1 in D;2) (Figs. 1 & 2). It was constructed to store and transmit water along the Wadi Shab Qais (D;2) around the northern flank of the Jebel el Khubtha mountain (C;2) in an elevated channel (40 in D;3) containing piping (Fig. 3) that continued over royal tombs (22, 23, 24 in C;2) to supply a large basin at its terminus (Fig. 4). This 'on-demand' system supplemented the water supplies of the urban core of the city (Bourbon 1999). Channels from this basin fed cisterns at the base of the mountain, adding water to



Figure 3. Elevated water channel/piping system on west face of El Khubtha Mountain.

that collected from rainfall runoff for urban housing needs and rituals at nearby tomb complexes. While runoff capture probably supplied the Zurraba reservoir, local spring sources, including Ain Mousa, were also important in the early phase of city development and may have also contributed water to the reservoir. Although reservoir water could be used to supplement the Siq channel, Ain Mousa water supplies were later switched to a piping system and the open channel was abandoned. Rainfall runoff and spring flow still enabled the Zurraba reservoir to supplement the Siq pipeline when required. Although the modern town has obliterated ancient hydraulic connections to and from the reservoir, there is no topographical constraint to a channel path which would have directed reservoir water into the open channel (or into a later pipeline system) to provide supplementary water supply. The Jebel el Khubtha pipeline, by contrast, appears to be the main *outflow* path for reservoir water in the area between Jebel el Khubtha and Wadi Mataha (B;2, C;2). Surplus water, after filling the cistern, was directed to the main city fountain (Nymphaeum 42, B;2) through either a pipeline or subterranean channel. Although no traces of this connection have been excavated, pipeline fragments in the area suggest this connection. From a systems point of view, the Zurraba reservoir served principally to maintain cistern levels in the royal tomb area by intermittent water release. The Ain Mousa spring, on the other hand, provided the continuous supply for the Nymphaeum through piping supported in a carved channel through the Siq (Figs. 5a & b) that replaced the earlier open channel. The Zurraba reser-

voir thus served as a backup system for rapid delivery of large volumes of water at short notice to the Jebel el Khubtha cisterns and served to augment the continuous, but declining, water supply to the Nymphaeum from the Ain Mousa spring during dry seasons. The ability to provide an 'on-demand' water supply from this backup source would have been most useful to large caravans entering the city that would place a sudden demand on water supply and usage.

Pipeline carrying capacity considerations: the Zurraba-Jebel el Khubtha system

While a spring produces a given volumetric flow rate, the limitation on how much can be transported by pipeline stems from its technical characteristics (diameter, internal roughness, slope and supply head). Piping design requires the spring output flow rate to match (or be less than) the theoretical carrying capacity of the pipeline. Examination of Nabataean pipeline designs yields insights into their ability to understand internal pipeline flow phenomena, and to construct solutions to overcome problems limiting maximum throughput. For an upper estimate of the volumetric flow rate that the Jebel el Khubtha pipeline system could sustain, it is assumed that the angle of about 0.005 shown by the elevated channel supporting the pipeline (Figs. 1 & 3) corresponds to the critical flow angle (Morris & Wiggert 1972). The maximum flow height within the piping is at critical depth equal to perhaps 50 per cent or more of the pipe diameter. This condition means that water flows in open channel mode through the piping, with an airspace above the water surface, and that the flow rate is maximum for given diameter and slope. This type of hydrostatically unpressurized flow *reduces leakage* between socketed pipeline elements, while providing the theoretical *maximum flow rate* for low angle piping functioning in either open channel or full flow mode. The maximum flow rate permissible then would be the critical velocity x piping wetted cross-sectional area. For a fall in channel height of about 40 m over the 8 km pipeline path around Jebel el Khubtha, the theoretical maximum volumetric flow rate is about 90 m³/hr for 20 cm diameter piping. In practice, owing to the many mortared joints between the 0.3 m terracotta piping segments (perhaps of

the order of 30,000) along the 8 km length of pipeline, and assuming, for a (very) conservative estimate, a 50 per cent leakage rate, the *deliverable* volumetric flow rate can be readjusted to at least 45 m³/hr. Good hydraulic practice, however, is to run open channel flow within piping at lower, subcritical Froude numbers ($Fr < 1$) to avoid flow instabilities caused by joint/channel wall roughness and sinuosity resistance. Froude number is defined as $Fr = V/(gD)^{1/2}$, where V is the flow velocity, D the hydraulic diameter and g the gravitational constant. Thus the *deliverable* flow rate needs to be adjusted further downward to produce a steady, open-channel flow within the piping. For Froude numbers of the order of 0.6–0.8, and with leakage effects included, a deliverable, stable flow rate of the order of 30 m³/hr could have been directed toward the Nymphaeum from the Jebel el Khubtha pipeline. If this long piping system were to function in full-flow mode, flow rate would be somewhat less than that derived from an open channel mode owing to internal wall friction. This generic observation was made in the early centuries AD (Vitruvius 1999: ‘. . . for a supply reservoir water height, long pipe lengths (containing full flow) diminish water transport amounts due to (cumulative) internal flow resistance effects . . .’; this result has been computationally verified (Ortloff & Crouch 2001; Fig. 2) to quantify Vitruvius’s comment. A piping slope less than that observed would have required larger diameter piping to match the spring flow rate and be subject to greater internal flow resistance. With a steeper slope, gravitational acceleration makes flows supercritical ($Fr > 1$). Rapid supercritical flows may be subject to intermittent zones of subcritical ($Fr < 1$) full flow caused by internal wall roughness and curvature resistance (causing velocity slowing) as well as transient hydraulic jumps that lead to pulsations in delivery. Such transient effects can lead to destructive tensile forces that weaken mortared piping joints. If flow-rate pulsations are transmitted to both the supplying and receiving reservoir, sloshing effects amplify unstable delivery rates. Transient changes in input head further amplify transient tensile forces and leakage from piping joints. The best piping design is therefore a partially full (open channel) flow at near critical conditions that empties water gently into a terminal reservoir. Selection of this pip-



Figure 4. Elevated settling basin typical of the El Khubtha channel/piping system.

ing design would be a measure of the understanding of hydraulic principles that were required to achieve a steady flow rate to the terminal basin in C;2 and would explain the high elevation of this pipeline (to maintain a low slope) around Jebel el Khubtha. The Nabataean design, given slope and pipe diameter, *closely matches* ‘best practice’ as its maximum carrying capacity lies *above* the 20–40 m³/hr capacity of the Ain Mousa supply spring assumes to be a possible (intermittant) supply source to the reservoir. It also provides for the largest possible flow rate from the Zurraba reservoir to meet ‘on-demand’ large flow requirements to the city centre. Additional benefits from the Nabataean design derive from use of partial flow in the piping which greatly reduces leakage rate as compared to a pressurized system. Since particles settle in the reservoir, no particle transport occurs to clog piping — this is particularly important as access to the high-elevation piping (25 m above ground) on the near-vertical Jebel el Khubtha mountain face (Fig. 3) would prevent easy cleaning. The combination of all these features indicates that much thought and experience went into the design of this system which achieved multiple goals that ensured not only system longevity but also rapid, stable, on-demand water delivery with minimum leakage.

Additional piping led to the Nymphaeum fountain to complete the Jebel el Khubtha circuit from the Zurraba reservoir. As the Nymphaeum was a major water supply to the urban core and market areas, much effort was employed to guarantee its year-round functioning. The Siq piping system was



Figure 5a. Piping elements on the north side of the Siq.



Figure 5b. Channel trough on the north side of the Siq for placement of piping.

supplemented, as required by occasional demand, by the long Jebel el Khubtha pipeline from the Zurraba reservoir.

Supplemental water-supply systems and water-supply redundancy

Cisterns and dams on Jebel el Khubtha (Akasheh 2003) (C;2) captured and stored rainfall runoff. Some of the upper-level cisterns appear to have channels leading to ground-level cisterns that fed urban housing or field areas to the west of Jebel el Khubtha, supplementing

the water supply from the Zurraba system. Intermittent springs located on Umm el Biyara (A; 1,2) may also have been important in ancient times; the Arabic name for this mountain translates as 'Mother of Springs'. As previously mentioned, the Siq open channel was abandoned in late Nabataean phases and replaced by a pipeline system (Figs. 5a & b) that extended to the area opposite the theatre district (B;1) and ended at the Nymphaeum. Thus *at least two* separate supply lines led to the Nymphaeum to ensure supply redundancy. The construction of the Siq pipeline system is generally attributed to Malichus II or his predecessors, Aretas IV or Obodas III, in the first century BC or early first century AD (Guzzo & Schneider 2002). Water demands south of Wadi Mousa were high on account of the nearby marketplace, theatre, temple and housing districts and significant water resources were available from the north side piping systems. A pipeline connection from the Nymphaeum to this area was therefore a logical use of surplus water for development of this area. A bridge most likely carried water from the north side of the Jebel el Khubtha system in the El Hubtar Necropolis area (20 in B;2) across the Wadi Mousa in the vicinity of the theatre (19 in B;1) but all traces are lost owing to extensive erosional flood damage. In addition to water delivered by these means, the theatre supply was supplemented from large, upper-level reservoirs in the Wadi Farasa area and pipelines originating from Ain Braq and Ain Ammon sources (Fig. 1). These again indicate built-in supply redundancy from multiple sources. Some of the larger reservoirs, therefore, appear to function in connection with a spring supply system and are situated to collect seasonal rainwater runoff. Reservoirs, therefore, were mainly to provide water for occasional peak requirements through piping or channel systems. Surface cisterns, on the other hand, appear to be opportunistically placed to collect rainwater runoff; other than seasonal rain recharge,

the numerous, widely-scattered catchments appear to serve local community needs for supplemental supplies of lower-quality water when piped water was not readily accessible.

Traces of a south-side piping system (Fig. 6) are found in front of the theatre. Two parallel pipelines continue past the theatre along the ridge (B;2) above the commercial district along the Roman *Cardo* (25), past Hadrian's Gate (43) [whose construction is attributed to Aretas IV], and the upper and lower marketplaces and the *Paradeisos* water garden (Bedal 2004) to locations above the Great Temple (28, Figs. 1 & 7) (Joukowski 2001; 2003). There it forms part of the water supply to structures located in B;2. The system consists of two separate pipelines that may indicate branch lines to separate destinations or a later elevation change that continues to Q'asr al Bint through the Great Temple to supply the Sacrificial Altar area. No excavations exist to connect the multiplicity of subterranean canals below the altar to a specific water source. Hadrian's Gate (43) separates the secular commercial district from the western sacred temple district containing the Great Temple, the Temple of the Winged Lions (26) and Q'asr al Bint. The gate reportedly had a gilded door to control traffic between sacred and secular parts of the city. The *Paradeisos* water garden west of the gate consisted of an open house situated on a platform island within a large water-filled basin. Bridge structures connected the island to outer precincts and greenery added to the city's elegance as indicated by reconstructions reported by Bedal (2004). Strabo (2000) mentions that the city '... contains many gardens . . .' consistent with recent excavation results. The basin walls contain overflow channels as well as supply piping that may emanate from both the *Nymphaeum* via a bridge connection and from a south side spring supply system. Overflow water from the garden may then have been directed to lower baths, chambers or



Figure 6. Dual pipelines continuing past the theatre to supply tanks (T) above the *Cardo*.



Figure 7. Great Temple on the south side of Wadi Mousa.

workshops (Browning 1982) close to the containing walls of Wadi Mousa before final discharging into the Wadi Siyagh. This is indicative of measures to use water in consecutive downhill structures. Distributed along this piping system, a number of elevated basins (T in B;2) lined with hydraulic plaster (Fig. 8) served as receiving basins; earth-fill mound structures extend from the tanks to the lower *Cardo* area and served to support the pipeline. As the basins are elevated at a height of 20 m on a bluff above the *Cardo*, there was sufficient head to provide pressurized water for



Figure 8. Fragment of one of the elevated water-collection basins (T) above the *Cardo* area.

fountains and basins in the market area below as well as for the Great Temple (and possibly Q'asr al Bint).

Since the south side of the urban core contains the marketplace area, water requirements were high; consequently, additional supplies were channelled to this area by means of an underground channel (B;1; B;2). This drew combined flows from Ain Braq and Ain Ammon about 5 km southeast of the urban core along the sides of the Wadi Farasa to the southern part of the city. Some, as yet, unexcavated branch of this system running through high-elevation channels may be part of the system that provided water to piping in front of the theatre. Water from these springs may have been supplemented by elevated cisterns in the Jebel Attuf area (B;1) in one of the many high places (12, 13 in B;1) of the city. Water for the Lion Fountain (14 in B;1) and al Hamman sacred pool area in the vicinity of elite tombs (16, 17, 18 in B;1) came from this supply line, which then continues on to the Great Temple area. It is clear that a continuous spring sup-

ply was part of the system from large elevated cistern on a plateau above the Tomb of the Roman Soldier (16 in B;1) (Browning 1982) also contributes rainfall runoff water to this system. Details of the Wadi Farasa water system in this area (B;1) have been investigated (Schmid 2002) and include large reservoirs and piping systems that not only serve local areas, but also have sufficient capacity to transfer water further west to the Great Temple area. Numerous channels, pipelines and multiple cisterns within, and leading from the Great Temple, indicate that water supplies within the temple were abundant (Joukowski 1999; 2001; 2003). Pipelines from the Great Temple to the marketplace area and the Q'asr al Bint region served as part of the water system. Ain Braq, Ain Ammon, the spring in Wadi Turkamaniya, multiple cisterns as well as a pipeline that may have crossed Wadi Mousa from the north side all contributed water to the Great Temple and Q'asr al Bint districts. A bridge abutment (45 in B;2) on the north side just west of the Temple of the Winged Lions contains some piping elements. These may represent just such a connection but the total configuration cannot be confirmed without further excavations.

Cognitive decisions: water-supply system network management operations

The incorporation of piping networks transformed the water system to meet the demands of a large urban population (estimated to reach 30,000: Guzzo & Schneider 2002). The Nabataean water system incorporated both intermittent, on-demand supplies piped from large reservoirs or drawn from cisterns and continuous supply systems from remote springs to provide the daily requirements of city inhabitants. These supplies were consciously regulated to meet demand fluctuations arising from special events in different areas of the city, superimposed upon daily requirements delivered to urban fountains. Water supplies were brought close to population concentration areas so that all were only a few minutes' walk away from fountains or supply basins. Regulation of the system required bureaucratic oversight, as decisions regarding storage or release needed not only day vs night but also seasonal adjustments. Efficiency dictated that no water could be wasted. As a consequence, transfer piping from north-side systems (Jebel el Khubtha and Siq pipelines to the Nymphaeum) provided water that could be transferred to south-side downhill locations for further usage or storage before final discharge into the Wadi Siyagh. In addition to spring systems mentioned thus far, water from springs in the Wadi

Kharareeb and Wadi Ma'aiserat north of the city may also have been channelled as far as the Great Temple and Q'asr al Bint areas although excavations have not yet verified the total configuration of pipelines and channels. Additional water supplies were available from the spring at Wadi Siyagh (A;2) and elevated piping or channel systems above tomb facades east of the Wadi Siyagh spring may also have fed water to a large terminal cistern (A;2) in addition to piping originating in nearby wadis containing springs. An elevated channel probably supplied large cisterns in the area from either rainfall runoff collected behind dam structures or through connection to the springs in this vicinity. The Wadi Siyagh spring, even today, is adequate for the local needs of scattered rural settlements in this area. The picture thus far developed is one of: a) exploitation of major springs for continuous supply of water to multiple city locations by long pipeline systems; b) reservoirs and cisterns recharged by spring input and runoff; and c) reservoir-pipeline systems designed so that supplemental reservoir water can provide on-demand release for special events or high seasonal demand. Such a well-planned system required equally well-planned management that involved measurement of stored water as well as flow rates. The simple rectangular geometry of major reservoirs made water volume easy to calculate. Measurement of flow rates may have used techniques developed by Hero of Alexandria (Ortloff & Crouch 1998) in previous centuries.

To add to this complexity, dam-based water storage presents yet a further aspect of Petra's water system. On the north side of Wadi Mousa, numerous high-status structures in the B;2 quadrant [Temple of the Winged Lions, Royal Palace (41), North Defense Wall and Fortress (35), Conway Tower (54)] are logically associated with a dam (d) at Wadi Turkamaniya (B;2) that may have trapped and stored sufficient runoff to provide water to the lower reaches of the Temple of the Winged Lions, although no excavation data is available. Prior excavations, however, reveal that lower portions of both the Temple of the Winged Lions and the Great Temple spanned the Wadi Mousa stream by a bridge. A destroyed bridge abutment nearby contains pipe-work that may have transferred water from the south to the north side of the city (or vice versa). Supply redundancy, achieved by laying pipelines from different water sources that crossed from one to another part of the city, is an aspect of the Nabataean design approach. This design philosophy ensures that water supply to any area *may be composed from different sources* depending upon variations in individual spring flow rates and reservoir or cistern supplies. Management oversight

must have been in place to monitor and to control the system network efficiently.

While cisterns are well dispersed through the urban settlement area, local sources describe a main underground channel starting from Ain Bebdbeh north of (D;3) and proceeding toward the convergence of Wadi Mataha and Wadi al Nassara (B;2), then running into the lower north side below the temple areas. The complete channel, mentioned by Taylor (2001), has not been fully explored but certainly added additional water supply to the north side.

The Nabataean mindset sought to utilize *all* water resources. On-site dams constituted yet further complexity to water management. Local histories mention the existence of large dams — one on the Wadi Mataha (Taylor 2001), the other on the Wadi al Nassara (Fig. 1). Remains indicate that these dams provided water storage from rainfall runoff within urban Petra. Most likely, dams were in place in other wadis to store water and to limit erosion or depositional problems within the urban environment. The water stored behind dams additionally served to raise the water table, supplying wells as a backup for the cisterns. A well exists in the Byzantine church east of (45 in B;2), and there may have been others; as yet, none are reported from the limited excavation data. Judging from Nabataean placement of the Wadi Mataha dam (d in B;2), it must have been an additional *third backup water source* to the Nymphaeum. Since the Ain Mousa spring could also serve to fill the reservoir behind the Wadi Mataha dam through the Wadi Shab Quais pipeline branch from Zurraba, the water level behind the dam could have maintained a sufficient level to provide backup water to the Nymphaeum throughout the year. The Nymphaeum could therefore be fed by water from the Wadi Mataha dam, by canal or pipeline from Ain Bebdbeh, by the pipeline along the western face of Jebel el Khubtha, and by the north side Siq pipeline. *This degree of redundancy indicates that planning for water-supply variations was a foremost consideration. It was addressed by a complex design that could tap into various water resources depending upon relative availability.* The redundancy guaranteed that if one of the supplies failed, others would be in place to guarantee water delivery to the urban core throughout the year. The redundant supply for the Nymphaeum illustrates cognitive planning to maintain the city's market and temple areas throughout the year, despite summer heat and lack of rainfall. The ingenuity of the Nabataeans must have been apparent to visiting traders who spread fame of the city's wealth, architectural accomplishments and water-management expertise to far corners of the known world.

Flood control, groundwater recharge and the Great Temple water subsystem

Floodwater drainage during the rainy season was a major concern. Since heavy rainfall and flooding characterize the Petra area, measures to divert Wadi Mousa floodwater from the Siq by means of a bypass tunnel (8 in C;1), a low dam at the Siq entrance and raising of the Siq floor near the entrance provided flood control. While this strategy had proved effective in deflecting small floods, deliberate infilling and accumulating flood deposits in the Siq continued to help protect against floodwater incursion. Large flooding events caused damage, but there were also ingenious ways to utilize the sudden water bounty. Storage dams across the numerous wadis intersecting the urban core served to reduce floodwater entry into the city while seepage from the impoundments recharged the water table allowing for wells during protracted drought. Thus some of the seepage from dam storage, canals and pipelines could be recaptured and used as (groundwater) defence against drought on a citywide basis.

The same idea could also be used on a more localized basis for elite structures. Within the Great Temple, an elaborate drainage channel system collected rainfall seepage and directed it to a nearby underground cistern with 50 m³ capacity (Joukowski 2001) located within the upper part of the temple structure. A channel from the upper part of this cistern conducted overflow water to lower level structures before exiting to Q'asr al Bint and Wadi Siyagh. Large channels in an upper room south of the Theatron (Joukowski 2003) of the temple most likely indicate the terminus of a subterranean channel from the Ain Braq/ Ain Ammon system (B;1, B;2). Additional water sources may have been available from springs in Wadi Kharareb and Wadi Ma' Aisert (Fig. 1) although intact piping has yet to be fully explored. Channel water, supplemented by cistern water to meet peak demands, was distributed to subsidiary open cisterns located on the eastern and western sides of the temple, then via subterranean channels under the lower temenos platform to rooms near the temple entrance stairway. Thus the cistern functioned as a reservoir adding stored runoff and southmost outer wall seepage water to the channel-delivered supply when required — much in the same way as previously-described reservoir-pipeline systems worked in tandem to meet occasional peak demands. Here the system is contained *within the temple itself*, and its importance as a major canal terminus and water distribution node, is made clear by the complexity of hidden channels, cisterns and

piping. The temple water system, capable always of providing ample water supplies for rituals, may have had special significance to demonstrate the premier role of religion in the lives of the Nabataeans. Only later, under Roman rule, are these supplies used for more utilitarian purposes, perhaps indicating a Roman predilection for practical concerns.

Many of the dams (d) shown in Figure 1 are located on top of mountains and are meant to store rain water to slow and limit water entry into the site during the rainy season. They are not cisterns *per se* but rather operate more as opportunistic water storage barriers to limit water entry onto the site below. They provide yet another source of emergency water supply as water trapped behind them adds to the conserved water supply of the city.

Technical innovations characterizing Nabataean piping systems

The piping systems east of the Great Temple reflect late Roman modifications to supply additional water for market and commercial structures along the Romanized *Cardo*. Sections of lead pipe running at the base of the platform of the Great Temple continued eastward towards this area. Lead piping usually indicates Roman manufacture so that identification with Roman modifications is probable. Low-fired clay pipes with relatively thick walls and socketed ends are also characteristic Roman work. Wall thickness can range from 1 to 6 cm while piping segments range from 30 to 100 cm in length. Internal diameter usually ranges from 20 to 25 cm for most typical urban pipes and, while the internal surfaces are generally smooth, the socketed ends involve significant constriction of the bore. Roman pipe diameters (Vitruvius 1999) are usually standardized throughout areas under Roman occupation; observed Roman piping in Petra generally conforms to standard categories. In contrast, some (but not all) Nabataean piping is made from high-fired clays with thin walls usually on the order of 5 mm or less with piping lengths of 30 cm or so. Short Nabataean piping segments are often the preferred design as they conform more easily to sinuous paths and allow for near flush connections that limit leakage. For applications where piping is laid in long excavated channels (e.g. Jebel el Khubtha mountainside, Siq walls), flush mortar infilling was used to reduce leakage. While the Great Temple is of Nabataean origin, elements of Nabataean piping remain along with Roman piping. Excavations have revealed thick-walled Roman piping butted onto earlier Nabataean piping, most likely to shunt additional water to market areas of the *Cardo*

from Great Temple sources. A further characteristic of Nabataean piping is that it is usually placed within channels cut into stone [including channels cut into mountain slopes (Figs. 3 & 6), Siq walls (Figs. 5a & b) and civic masonry] then mortared over to yield a water seal and improved aesthetics for civil structures and greater security (protecting the supply). Subterranean channels are found elsewhere in the Nabataean domain (Levy 1999), and the concept of hiding water channels and sources served as a defensive measure to protect vulnerable water supplies — particularly spring sources distant from the city centre.

Nabataean short piping elements are characterized by a relatively slight constriction at the junction and, within the piping interior, by sinusoidal ripple patterns (Fig. 10) with wavelengths of about 1.0 cm and amplitude of 3 mm. Piping in the Great Temple area and theatre shows rippled interior patterns of this type. Experiments (Walsh 1980; Cary *et al.* 1980) indicate drag reduction for ripple geometry similar to that observed in Nabataean piping elements. The use of such drag-reduction methods in Nabataean piping designs permits a higher flow rate (on the order of 5 to 10 per cent) for the same head than for smooth interior piping. This may constitute the earliest empirical observation that minor internal roughness in piping can increase flow rate, particularly where connection joints are smooth. Questions arise as to whether the ripple patterns are deliberate or simply a byproduct from manufacturing processes, but their appearance in conjunction with smoother joint connections may represent a design refinement to improve flow rate — perhaps revealed just by empirical observation.

The piping system on the north side of the Siq (Fig. 5b) contained four open drinking basins capable of trapping particles, with easy access for removal. Dam systems also served to settle particles to improve water quality before it was delivered to fountains. Long pipelines (such as the Wadi Shab Qais system) are es-

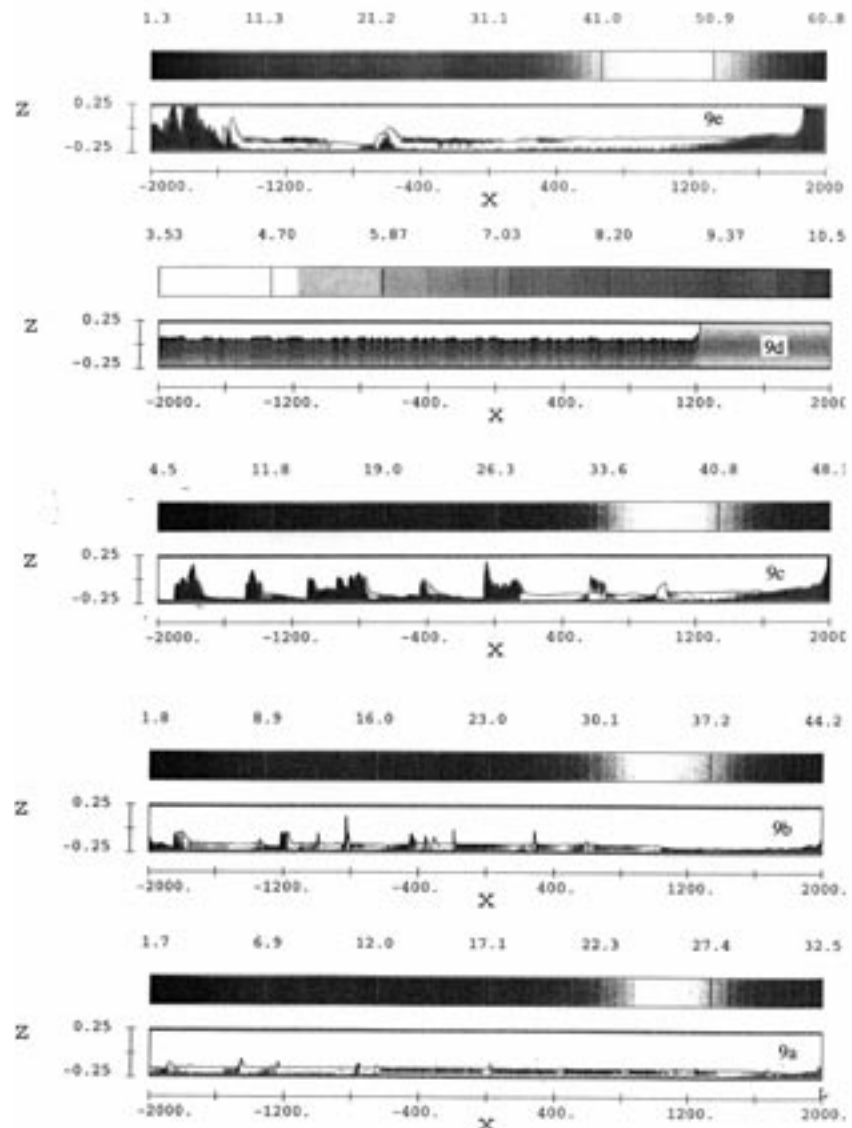


Figure 9. FLOW-3D calculations of a rectilinear model of the Siq piping for entry full flow input flow rates of 1.0 (a), 2.0 (b), 5.0 (c), 10.0 (e) ft/s (0.305, 0.610, 1.52, 3.05 m/s) velocity indicating internal flow development for the observed wall roughness distribution. Figure 9d shows results for smooth interior piping at 1.52 m/s initial, full flow inlet velocity (inlet at right).

entially immune to particle clogging effects since the upstream reservoir at Zurraba serves as a settling tank. This reservoir appears to have multiple sections that may represent some form of internal particle settling capability; however, no detailed excavations of silt types are available. Thus water-quality improvements went together with reduction of sediments trapped in pipelines and provided substantial benefits to the continuous operation of the Petra water system.

If the piping lengths are very long, wall friction limits flow rate and increases in pressure head do not



Figure 10. Typical rippled wall pattern within the interior of Nabataean piping.

translate proportionately into flow rate increases (Ortloff & Crouch 2001). For this reason, long pipelines, where feasible, are usually interrupted by open basins placed along their length, effectively to create short piping segments between (cleanable) head basins. Such a system permits higher flow rates than a continuous pipeline with no intermediate basins. Although this practice is observed in Roman piping networks (Ortloff & Crouch 2001), it is probably an innovation of pre-Roman times. The piping on the north side of the Siq provided the main potable water supply. The south-side channel, on the other hand, was probably meant for animal watering purposes and may have been supplied by a channel from Ain Braq and supplemented from a cistern atop the bluffs with a drop hole to this channel (C0, Fig. 1). This may have fed the south-side systems in the theatre district but it is not possible to verify this connection at present.

The Siq piping system — flow stability considerations

Nabataean pipeline design solutions can best be illustrated by a computer analysis that reproduces internal flow details. To examine flow stability in the Siq north-side piping, sample computer models were made of a 1220-m-long section with 14.0-cm-diameter piping inclined at a 2.5 degree angle with and without internal roughness. The Ain Mousa spring had a high flow rate which the Siq piping system must have accommodated. A number of sample FLOW-3D computer runs (Flow Science Inc. 2003) were made for velocities of 0.305 (Fig. 9a), 0.610 (Fig. 9b), 1.524 (Fig. 9c), 3.05 (Fig. 9e), 6.10 and

9.15 m/s using the measured slope and wall roughness. One criterion for determining an acceptable flow rate relies on flow stability (i.e. is flow smoothly delivered to a destination point without pulsations?). A second criterion asks if the flow delivered to an open basin can be successively transported to the next pipeline segment without spillage and if a stable free surface flow exists in the piping that can transfer water smoothly to sequential pipelines interrupted by intermediate basins without sloshing. For this to occur, pipeline segments between basins must have the same resistance characteristics, similar internal flow patterns and the same entry conditions. A third criterion requires that the flow rate is sufficiently high to accommodate urban-core water needs for a population of 30,000. A further criterion is minimization of leakage. Here partial (internal open channel) flow is preferable as hydrostatic pressure effects causing leakage are reduced.

The results indicate that flow velocities up to 1.52 m/s (Figs. 9 a, b, c), with prescribed wall roughness as shown in Figures 5a and 10, produce an open channel flow within the piping but with an apparent unsteady delivery rate. This is manifested by random water peaks that translate down the piping leading to an unsteady delivery resulting in possible sloshing and spillage in open basins along the length of the piping. For piping with a smooth interior at this flow rate a smooth delivery flow rate can be achieved (Fig. 9d), but at the expense of a longer pipeline segment exposed to hydrostatic pressure and increased leakage. At a higher 3.05 m/s flow velocity (Fig. 9e), effects of the roughness-induced, randomly-distributed water height changes disappear over much of the piping length leading to smooth free surface flow. This high speed flow turns back to a full flow after nearly 1200 m owing to cumulative wall friction effects (Fig. 9e). This negative feature can, however, easily be removed by the 'head reset' feature so that shorter length pipe segments connect open basins with open channel flows up to 400 m in length. This would require at least four north side basins within the Siq. Without open basins, an uninterrupted pipeline would contain an unsteady flow and require a large downstream settling basin to trap particles before further distribution. The Siq excavator (Bellwald 2004, pers. comm.) has recently confirmed that there *are* four open basins within the Siq. These would hence not only have provided drinking water for entrants to the city but *also* provided an elegant yet practical solution to the problem of flow stability. Water velocity of *c.* 3.0 m/s is adequate to prevent major instabilities and since the supercritical flow fills about 25 per cent of the piping cross-section (at normal depth) and allow a (very conservative) 50

per cent for leakage, spillage and evaporation, then the *deliverable* Siq flow rate approaches 36.0 m³/hr, well within the maximum Ain Mousa spring flow rate. Since the (on-demand) Wadi Shab Qais water-supply capability can be around 30 m³/hr, maximum north-side water supply that could be carried through these two piping systems is estimated at about 60 m³/hr. Some control over entry flow rates into each piping system must have been in place, and the storage or release of the Zurraba reservoir must have been adjusted in line with seasonal spring or runoff supply. The predicted 35 m³/hr flow rate is consistent with current-day Ain Mousa flow rates (Markoe 2003) of 20–40 m³/hr although past rates cannot be known with certainty.

The Siq and Jebel el Khubtha pipelines are of different designs and demonstrate the ability of Nabataean engineers to produce designs to suit different purposes. While the Jebel el Khubtha and Siq piping systems have a 7X slope difference (the former by selective design, the latter dictated by topography), the presence of head reset basins for the Siq system permits use of short piping lengths to maintain low flow resistance, and so sustains a high flow rate. Although Siq piping internal open channel flows are supercritical ($Fr > 1$) owing to the steep slope, there is no possibility of achieving near-critical maximum flow rates given the slope and diameter of the pipes. The net result is a design that meets criteria for a high flow rate and delivery stability. The long, uninterrupted Jebel el Khubtha pipeline maintained a high subcritical ($Fr < 1$), open channel flow that gave a large flow rate without instabilities. The Zurraba reservoir acted as a settling tank to remove particles, and the low velocity of 1.25 m/s provided stable delivery, a flow rate close to the maximum theoretical value, reduced leakage, elimination of clogging effects and sufficient height at the terminal basin to supply further piping. The hydraulic design differences of these two pipeline systems indicates an understanding of different design options for different flow problems. The fact that few, if any, Roman additions were made to the water-supply situation may be an indication that the Nabataeans had already exploited all available water sources and that Roman technological improvements could not significantly improve upon existing Nabataean technologies.

Petra per capita water availability compared to Roman standards

For estimates of total water flow into the city, we may conservatively assume a north-side supply approxi-

mately one third that of the south-side rate owing to the less robust south-side springs. Assuming a combined flow rate between the Siq and Wadi Shab Qais reservoir release lines to be about 40 m³/hr, then the city could receive *at minimum* an estimated 50 m³/hr from these sources. Additional sources [Ain Braq (0.8 m³/hr), Ain Dabdabah (2.5 m³/hr), Ain Ammon and Ain Siyagh (<1.0 m³/hr)] increase this estimate. Storage water and other springs would add yet further capacity to arrive at a yet higher flow rate — perhaps 100 m³/hr in total if less conservative leakage estimates are used. For a city of 30,000 inhabitants (Guzzo & Schneider 2002), at least 0.04 m³/day (40 litre/day) would have been available on a per capita basis, which is minimal to maintain hygienic standards for an urban population. If we add public use in the form of fountains, watering troughs, baths, water gardens and workshops, per capita water availability would have been well within the Rome urban water usage rate of 0.6 m³/day per person (Butterfield 1964). Survival in hot climates requires water intake per person of about 0.003 m³/day. Surplus water beyond human survival needs is hence available by these estimates. Estimates for water storage from dams and cisterns on Jebel el Khubtha alone (Akasheh 2003) are 0.36 m³/person for an extended period. With a personal consumption rate of 0.003 m³/day, a two-month emergency supply is available through the Jebel el Khubtha cisterns were spring flow rates to decline precipitously. A similar calculation shows that Zurraba reservoir contains about three weeks' emergency supply. Additional cisterns and dams on site, particularly those of the Wasi Farasa system (Schmid 2000) add yet further reserves, totalling several months' supply. While per capita water supply for Petra were somewhat lower than that of Rome, the amounts supplied on a continuous basis would have been more than sufficient to maintain quality living standards.

The city underwent major construction in the period 50 BC to AD 100 during the reigns of Obodas II (III) and Aretas IV (with construction of the Treasury, Q'asr al Bint, Temple of the Winged Lions and Theatre), and Roman and Greek technologies most probably influenced the water-system design. The availability of advanced Roman surveying techniques used for aqueduct design (Lewis 2001) would have been particularly useful in constructing long-distance lines of prescribed slope to and within Petra. While the design capability to achieve flow balances remains elusive owing to our fragmentary knowledge of ancient hydraulics, some hints of capability to measure water flow rate exist (Cohen & Drabkin 1966; Orloff & Crouch 1998) in works of Hero of Alexandria. These

may have found use in later hydraulic planning by the Nabataeans — particularly to match spring flow rates with piping flow rate capacity.

Nabataean overall water-system design strategy

Early use of spring-fed pipelines in Hellenistic cities of Ionia, mainland Greece and the Greek colonies (Crouch 1993) and in contemporary Roman cities indicates that pipeline technology was well developed in many parts of the ancient world and was available for assimilation into Nabataean water system. The Nabataean systems, however, are unique in that water conservation is practiced on *a much larger scale* and intermittent supplies from seasonal rainfall were exploited to sustain the city through dry seasons. In essence, *the Nabataeans utilized all possible above-and-below ground water supply and storage methodologies simultaneously*. While water storage in contemporary Hellenistic cities also emphasized cisterns for household use, the Petra systems advanced this technology to *citywide* systems with elaborate dams and cisterns that served both water storage and flood control purposes. Water storage in aquifers was promoted through dams; this allowed for use of wells as a backup system should all other supplies fail. Provided a cistern could be made deep enough, it would be resupplied from groundwater, a technique well known in Bronze and Iron Age cities of the Near East.

Summary and conclusions

A comprehensive water-supply system of dams, cisterns, channels and pipelines exploited springs as well as rainfall runoff. While some of the technology must have been borrowed from contemporary cities, the limited water resources at Petra, combined with the complex topography led to innovations in the use of water-storage methodologies on a *citywide* scale where stored runoff water provided a sizeable fraction of yearly requirements and served as a backup to the many springs. Examination of two different pipeline systems with very different slopes and delivery requirements (one on-demand and the other continuous flow) indicates that technology (and experience to employ it) was in place to provide different designs that minimized leakage, maximized the flow rate, minimized particle ingestion and clogging and eliminated transient flow instabilities. The Siq pipeline incorporated water purification by means of four well-placed settling basins which also solved a complex flow stability problem. The range of solutions adopted confirms that a hydraulic design methodol-

ogy was in place and was applied with great cognitive skill to solve complex hydraulic problems.

It is traditional to look for Roman technical advances that improved the Nabataean system, but few are found. This indicates that Roman engineers may have viewed the Nabataean system as near-optimum. In that case, it is likely that the several water-management techniques observed by the Romans may have been borrowed by them and applied to their desert cities and outposts. It is clear that the success and longevity of Petra depended upon its innovative water-system design which in itself constitutes a vital chapter in the history of water management in the ancient Near East.

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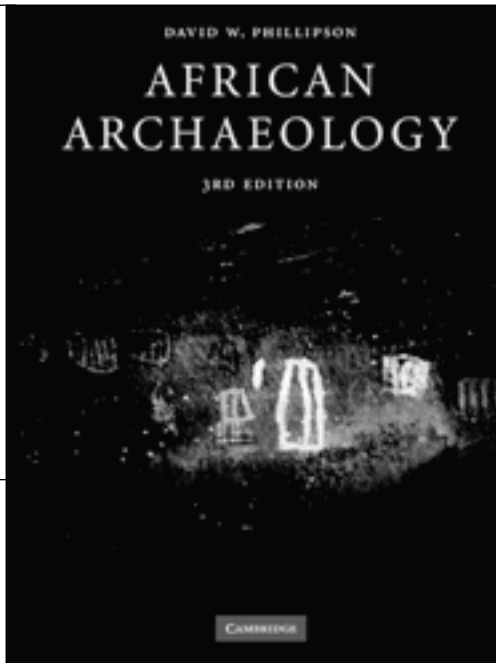
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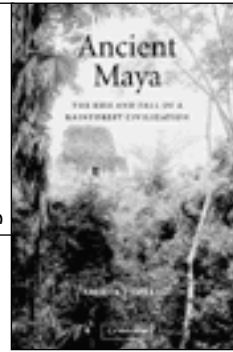
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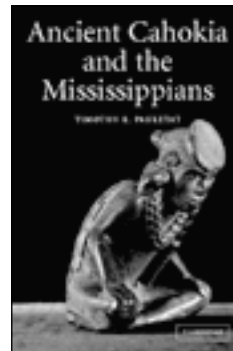
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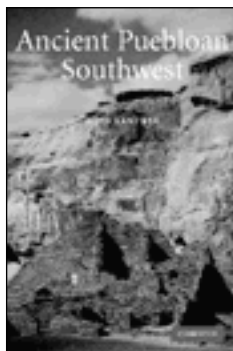
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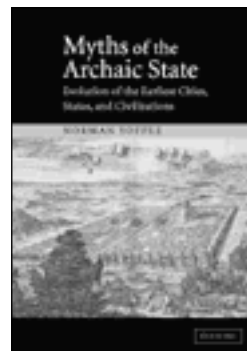
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