SĪQ AL-MUDHLIM STUDY SURVEY, 2002

Petra National Trust

Introduction

In 2002 Petra National Trust (PNT) carried out a study in Petra in co-ordination with the Department of Antiquities of Jordan (DoA) and a specialist team of consultants in the private sector, Middle East Engineering Management (MeeM). The study assessed the impact of flash floods and the possibilities for flood protection of the Wādī Mūsā along its diversion into the Wādī al-Mudhlim and Wādī al-Maṭāḥa. The Wādī Mūsā catchment area extends east of Petra to both the north and south (**Fig. 1**).

The study comprised three stages: to collect data (i.e. topographic and archaeological survey) and review pervious works; to undertake the hydrological and hydraulic investigations and finally to explore the flood mitigation and management options. As a result of the work, the archaeological remains of the area were recorded and preliminary designs were developed for flood protection; four main groups of structures were proposed, two dams, one pond and three check dams, and the clearance of collapse within the Sīq al-Mudhlim tunnel was strongly recommended.

Overall the study area included the entire catchment area for the Wādī Mūsā, but for the topographic and archaeological surveys it was narrowed down to the courses of the Wādī Mūsā, Wādī al-Mudhlim and Wādī al-Maṭāḥa, beginning at the Mövenpick Hotel arched culvert (UTM E194900, N970550), continuing via the Nabataean tunnel (Sīq al-Mudhlim) at the entrance to the Sīq and ending at the Nymphaeum inside the central Petra basin (UTM E192600, N971020).

The authors and contributors of the information contained in this report are Ueli Bellwald, Ma'an al-Huneidi, Munther Kharouf, Dr. Adnan Salihi and Ibrahim Najjar. All the complete and detailed information regarding the studies and the location and details of the proposed flood mitigation measures are on file in Amman at PNT and DoA.

The Topographic Study

The topographic survey, which covered a length of just over 5.1km and an area of 152,559m^2, produced final drawings which formed the base for the other field studies. The study area was divided into 12 sectors (**Fig. 2**) and one-metre contour maps were developed for each sector together with a general plan for the whole site. Over 4500 points were taken and the elevation at the beginning of the survey (sector MS1) was 1062m, dropping down to 875m at the Nymphaeum. The tunnel was treated with particular care and a longitudinal section was drawn to show the ceiling features.

The Archaeological Study

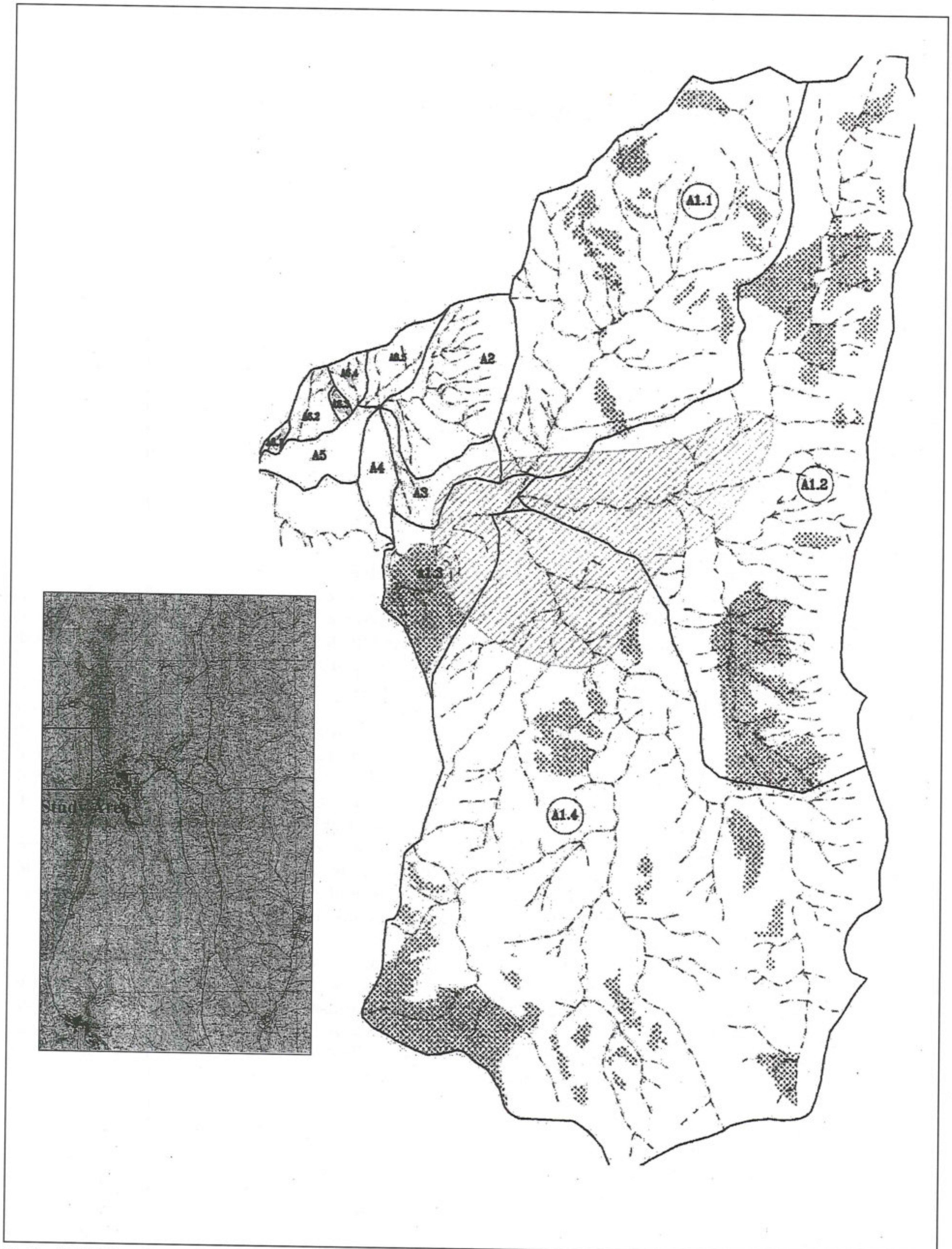
The archaeological survey included the flanks of the wadis along with the wadi beds, so that any connections between installations in the wadi beds and those along the banks would be recognized.

All ancient structures were recorded on the project maps, described and preliminary identifications made. A background study of all reports from the 19th and early 20th century (Burckhardt 1822; De Laborde 1830; Brünnow-Domaszewski 1904; Musil 1907; Dalman 1908; Bachmann-Wiegand 1921; Horsfield 1938) was carried out.

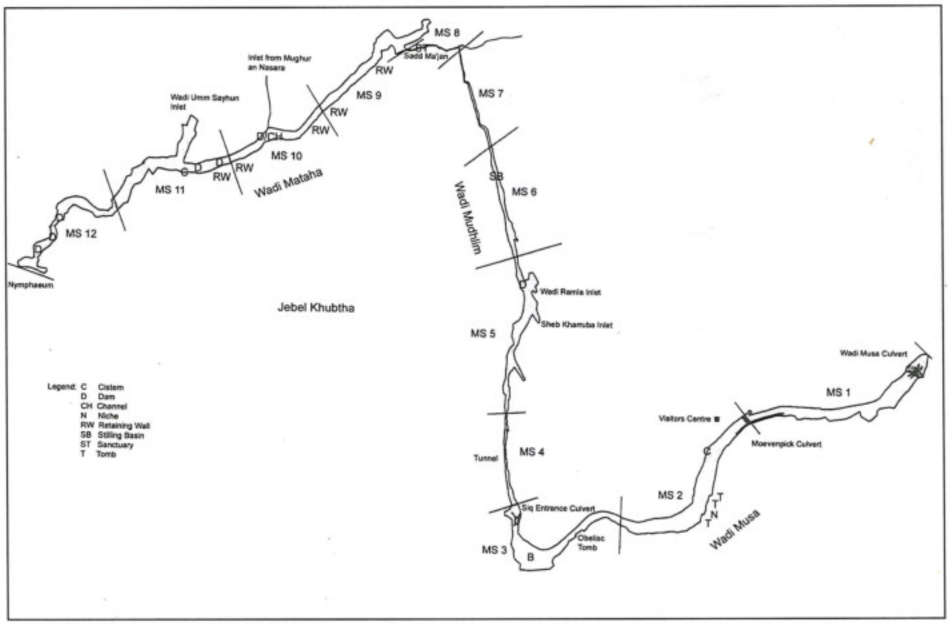
The results of the archaeological survey are presented below, sector by sector, with a short description of the most important elements recorded and an initial interpretation of function.

Sectors MS 2 - MS 3, Necropolis Area

During the Nabataean period, the entire southern and eastern part of the northern bank of the Wādī Mūsā in both sectors was occupied by a necropolis. Today about 60 structures have been identified, amongst which 12 border the wadi bank. From this group of ancient structures, four tombs and one sanctuary are partially buried by wadi rubble (**Fig. 3**). Estimates, based on patches of bedrock exposed in the centre of the wadi bed and other fully exposed structures located higher up the bank (such as the Dromos Tomb with the snake and horse bas-relief), suggest that these structures might be buried by up to two metres or more. Ac-



1. The Wādī Mūsā Catchment Area at Petra with the whole study area inset.



2. Map of the area surveyed showing the sectors and the location of the recorded archaeological remains.

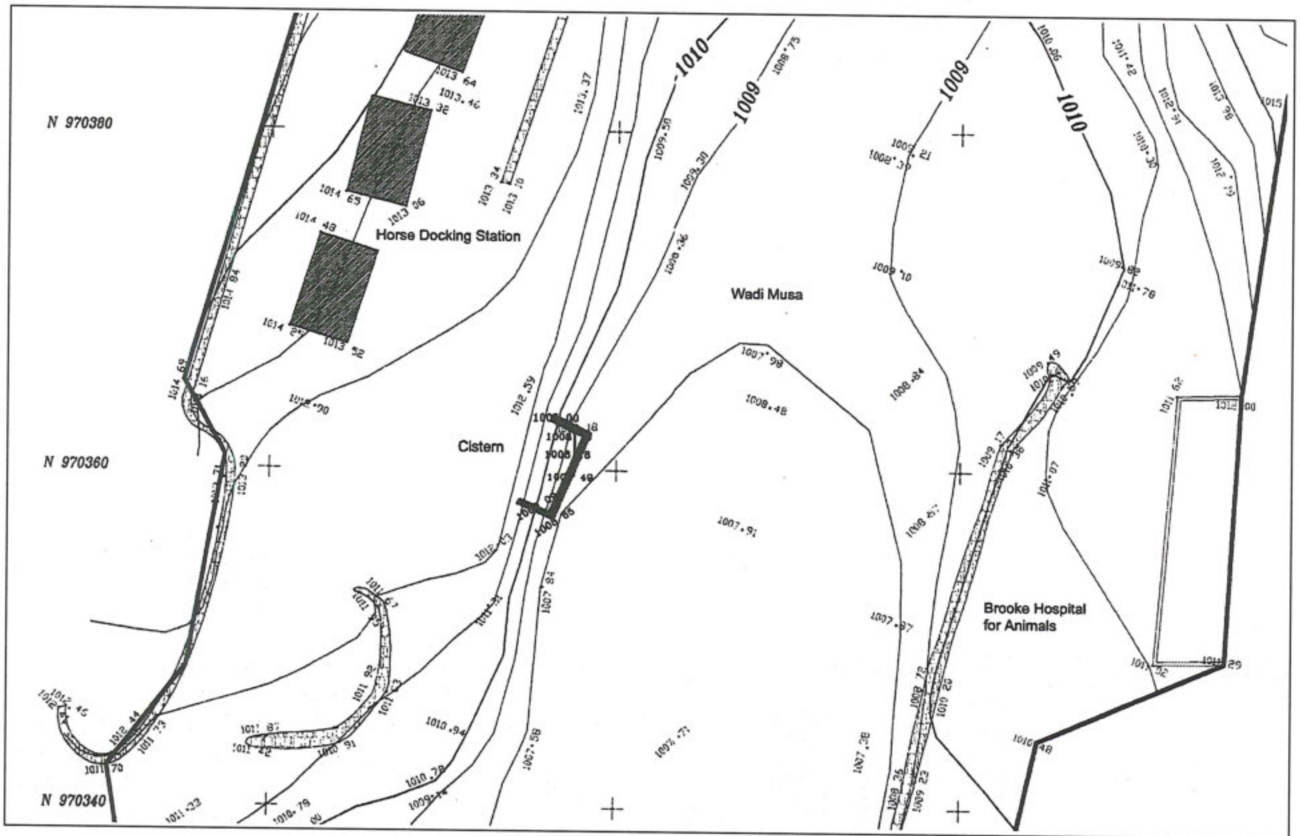
3. Partially buried tomb façade in the southern bank of sector MS 2, with an extended forecourt cut into the cliff.

cesses to all structures at present day wadi level are partially obstructed by debris, for example the Bāb as-Sīq Triclinium below the Obelisk Tomb. Here the disproportion between the width and the height of the façade implies that not all of it is visible and a thorough analysis of the architectural elements shows that none of the pilasters, quarter-and half-columns have bases, which means they were planned to reach further down. Well-preserved quarry trenches at the downstream end of the terrace, in front of the façade, also imply that the façade was left unfinished since quarry trenches were normally removed in front of finished monuments. The flood of 2nd May 2001 showed that the wadi bed in front of the Bāb as-Sīq Triclinium can be filled to the level of the terrace with washed-in debris within only two hours. If the façade was planned to reach further down, the conclusion must be that the bottom of the wadi bed then was at a much deeper level than is evident at present.

That the Nabataean necropolis extended onto the northern bank of the Wādī Mūsā is demonstrated by the large structures of the courtyard tomb (Triclinium No. 4) in the precinct of the Guest House of the Crowne Plaza Hotel. Besides the Urn Tomb in the western cliff of Jabal al-Khubtha (جبل الخبثة), this tomb is the only one in Petra with flanking porticoes chiseled in bedrock. This tomb, with its outstanding architectural design, highlights the importance of this little understood necropolis. Close to the northern bank of the wadi bed only one ancient structure is actually visible. It is a rather well-preserved cistern, located directly below the access to the horse docking station by the entrance gate (**Fig. 4**). Its front wall, towards the wadi bed, has been washed away leaving the internal structure of the cistern clearly visible. It is 4.6m wide, its interior was fully plastered and was covered by semicircular arches that supported a ceiling of sandstone slabs. The original bottom of this cistern is buried under wadi debris and for the moment, the context in which this cistern functioned remains unknown.

Sector MS 3, The Detention Basin

The most important element detected in sector 3 is the flash flood detention basin (**Fig. 5**). This enormous basin covers the entire area of the curve where the course of the Wādī Mūsā changes from east-west to south-north. Along the northern bank, the basin was closed by the dam of the high level road, built by the Nabataeans between 50 and 25 BC as part of the construction of the paved street in the Sīq. The course of this road and its dam can



4. Plan of the visible structures of the cistern in the northern bank of the Wādī Mūsā, just below the horse docking station.

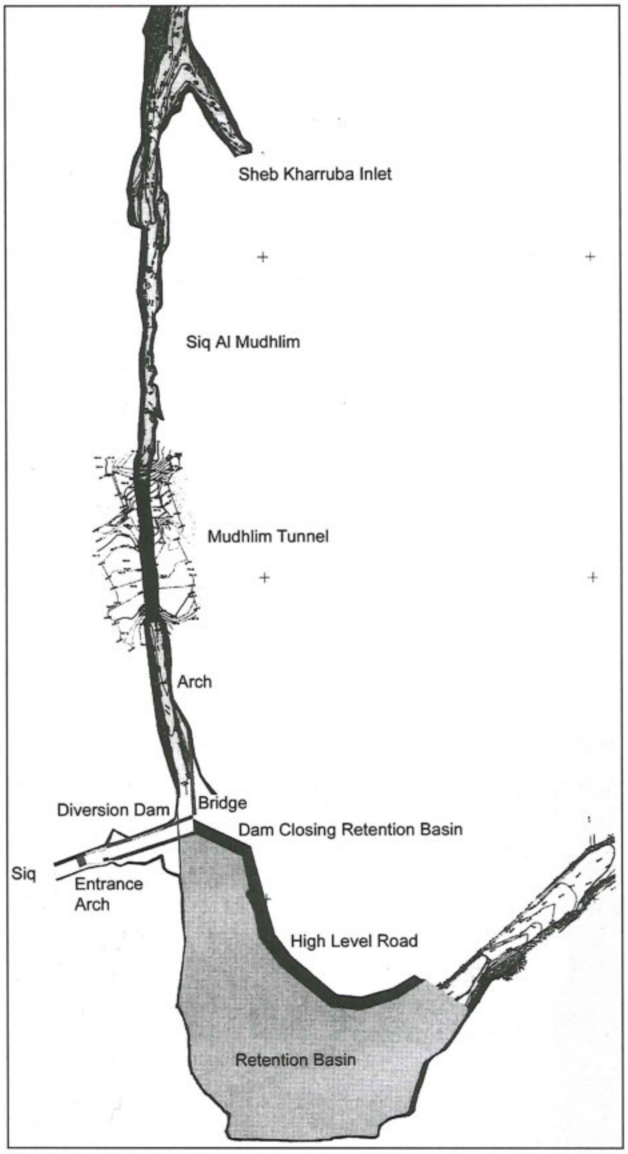
still be followed from the beginning of the curve down to the dam at the entrance to the Sīq and patches of its pavement may still survive below the debris that covers it. The basin's southern side was delimited by the cliff of Jabal Madrass (جـبل مـدرس). The layout of the basin by the entrance to the Sīq and the tunnel at the time of its construction in the late first century BC has already been explained elsewhere (Bellwald 2000 and 2003:55) (**Fig. 6**). Calculations based on the information given by Bachmann and Wiegand as well as the visible remains, make it clear that the bottom of the basin was at least two metres lower than the bottom of the tunnel. This difference suggests that the basin functioned as an enormous settling tank, preventing boulders, trees and other debris from obstructing the free outflow of water through the tunnel.

An important discovery was made between the box culvert by the Sīq entrance and the upstream mouth of al-Mudhlim tunnel: cut into both walls of the outflow channel leading from the basin towards the tunnel a pair of abutments can only be the remains of a collapsed arch (**Fig. 7a, b**). This arch was erected 37.8m upstream of the opening of the tunnel, with a span of 5.5m and a width of 1.3m. Since neither bank above the cliffs shows the slightest remnants of any construction such as a water channel, it can be concluded that the arch was not erected to support any structure.

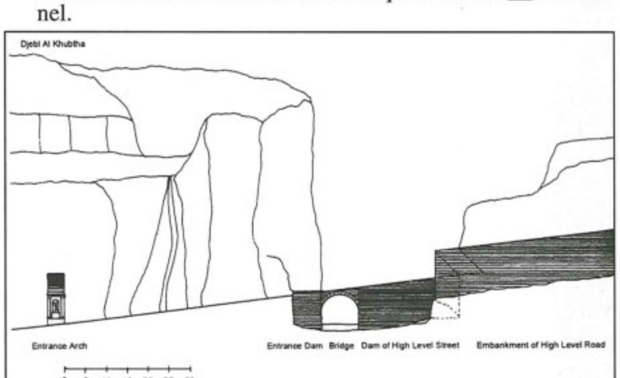
It is located at a slightly greater distance from the ancient bridge crossing the Wādī Mūsā than is the entrance arch to the Sīq and while a functional reason for the erection of this arch seems improbable, a commemorative one related to the entrance arch is much more likely. It could, for example, have carried an inscription commemorating the construction of the entire flash flood diversion system, the mouth of the tunnel being much too far from the bridge for such an inscription to be seen. Such commemorative inscriptions are known from the diversion tunnel in Seleukia Piera, the port of Antiochia (modern Antakya in Turkey). With the discovery of the existence of a second arch, a new component may be added to the design of the comprehensive infrastructure in and around the Sīq . With two monuments focused on the bridge crossing the Wādī Mūsā, offering spectacular and unexpected views, the basic plan of the infrastructure shows itself to be completely determined by Hellenistic urban systems.

Sector MS 4, The Tunnel (Sīq al-Mudhlim)

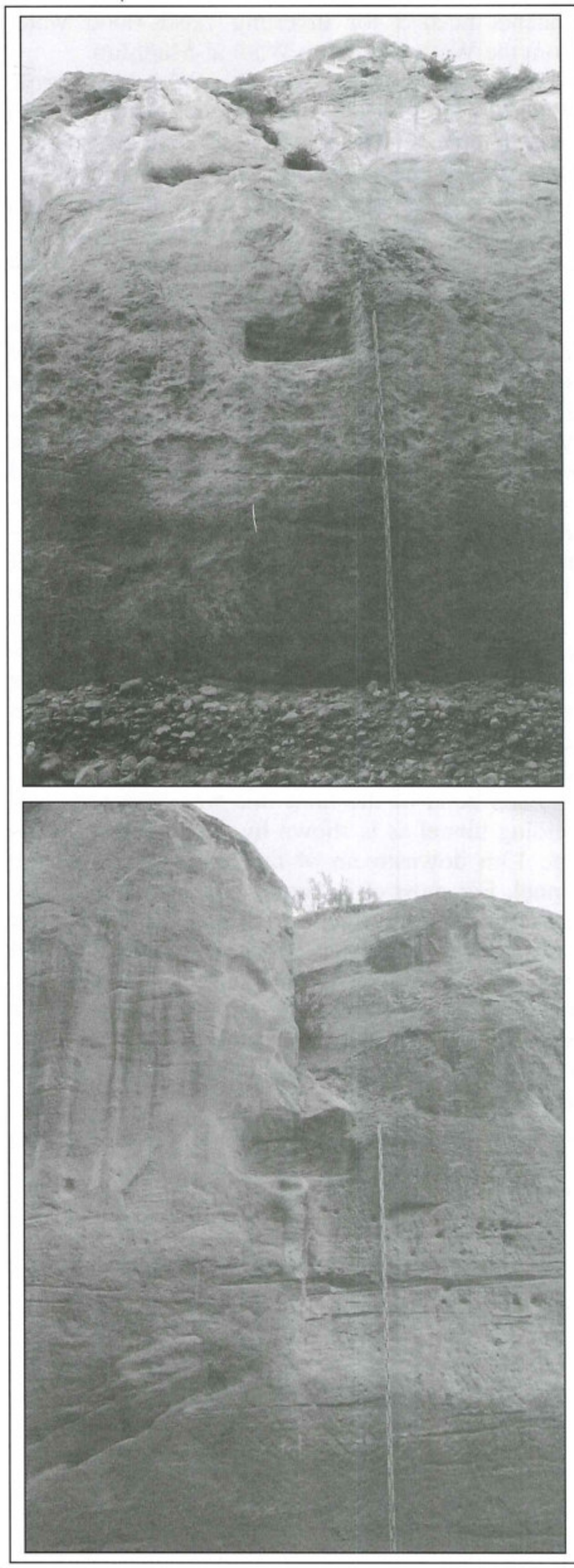
Sector 4 includes the tunnel and its inflow and outflow channels, which comprise the three com-



5. Plan of the retention basin at the bottom of sector 3, the infrastructure at the entrance to the Sīq and the Mudhlim tunnel.



6. The situation at the entrance to the Sīq after the completion of the infrastructure in the second half of the first century BC. Elevation of the dam crossing the bed of the Wādī Mūsā diagonally and of the retaining wall of the high level road along the axis of the uppermost 115m of the paved street in the Sīq.

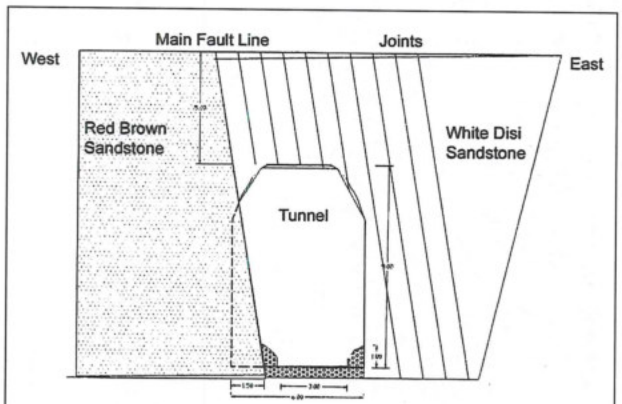


7a, b. The western (left) and the eastern (right) abutment of the arch spanning the outflow channel leading from the bridge to the tunnel.

ponents needed for diverting flash flood water from the Wādī Mūsā into Wādī al-Mudhlim.

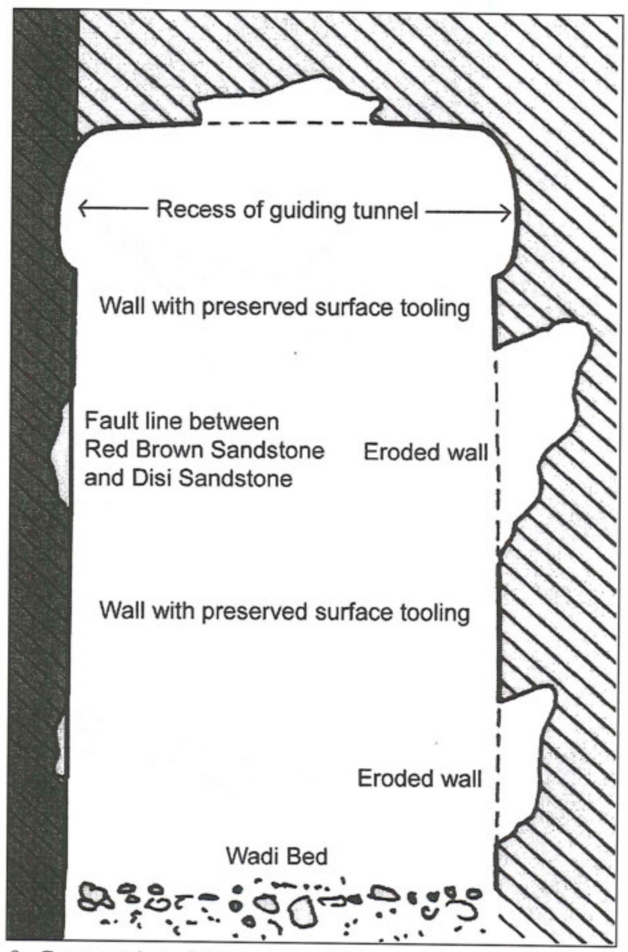
A bedrock bar separates the Wādī Mūsā from Wādī al-Mudhlim and this was cut down to form an open channel for as long a distance as possible. Only the highest, central part of the bar was pierced by the tunnel and close examination of its walls and ceiling has allowed a detailed reconstruction of how this was achieved. At both ends of the tunnel the surface tooling of the bedrock is preserved, but unfortunately for most of its length the original chisel marks have been lost due to partial collapse. On the right-hand (east) wall at the upstream mouth of the tunnel, surface tooling is preserved for about 20m. It shows that this side was worked down vertically whereas the left-hand (west) wall is inclined toward the west, thus making the tunnel narrower at its bottom (**Fig. 8**). Detailed inspection of the surface of the west wall shows clearly that no chisel marks have been eroded away, but that there never was any surface tooling. The slope of this wall and its lack of any surface tooling indicate that the original engineers used the fault line between the hard red-brown sandstone and the weak white Disi sandstone to align the axis of the tunnel.

Each bend of the fault line was followed by a guiding tunnel as is shown by the correction of its line 13m downstream of the upper mouth of the tunnel. For most of its length, the left wall simply consisted of the surface of the fault as it was after the covering white sandstone had been chiseled away. At the downstream mouth the axis of the tunnel no longer follows the fault line but runs in a perfectly straight line; hence there is surface tooling, which is preserved and covers both walls for more than 30m.



8. Cross section of the tunnel at its upstream mouth, sketch looking downstream. The left wall shows the inclination of the fault line between the red brown sandstone and the white Disi sandstone, which differs considerably from the projected vertical wall.

At both ends of the tunnel the surfaces with preserved chisel marks reveal that the uppermost 150cm of the walls were more deeply carved into the bedrock, by 2-5cm. The bottom line of this slight recess on both walls is parallel to the crest of the ceiling vault (**Fig. 9**). These differences in the surface tooling point towards various steps in the work during the making of the tunnel. They show clearly that work started with driving a guiding tunnel through the bedrock. This guiding tunnel ran along what became the ceiling of the tunnel; the work being executed from the top down, a procedure well known from the rock carved façades. As there are no recesses visible in the ceiling, the guiding tunnel must have been cut across its entire width in one work step. Once the guiding tunnel was finished, the tunnel proper was cut down using the technology applied in Nabataean quarries: a succession of parallel quarry trenches was incised into each successive layer of the bottom of the tunnel. These primary trenches, spaced roughly 40cm apart, ran at a right angle to the longitudinal axis of



9. Cross section of the tunnel at its downstream mouth, sketch looking downstream. The recesses of the guiding tunnel directly below the ceiling are clearly visible on both walls.

the tunnel. Next, secondary trenches were cut down parallel to the longitudinal axis of the tunnel, spaced from 50 - 80cm apart. Finally the rectangular blocks thus formed in the network of quarry trenches were split from the bedrock by two wooden wedges moistened with water. The ends of some of these quarry trenches are still recognisable as small, vertical recesses in the tunnel walls.

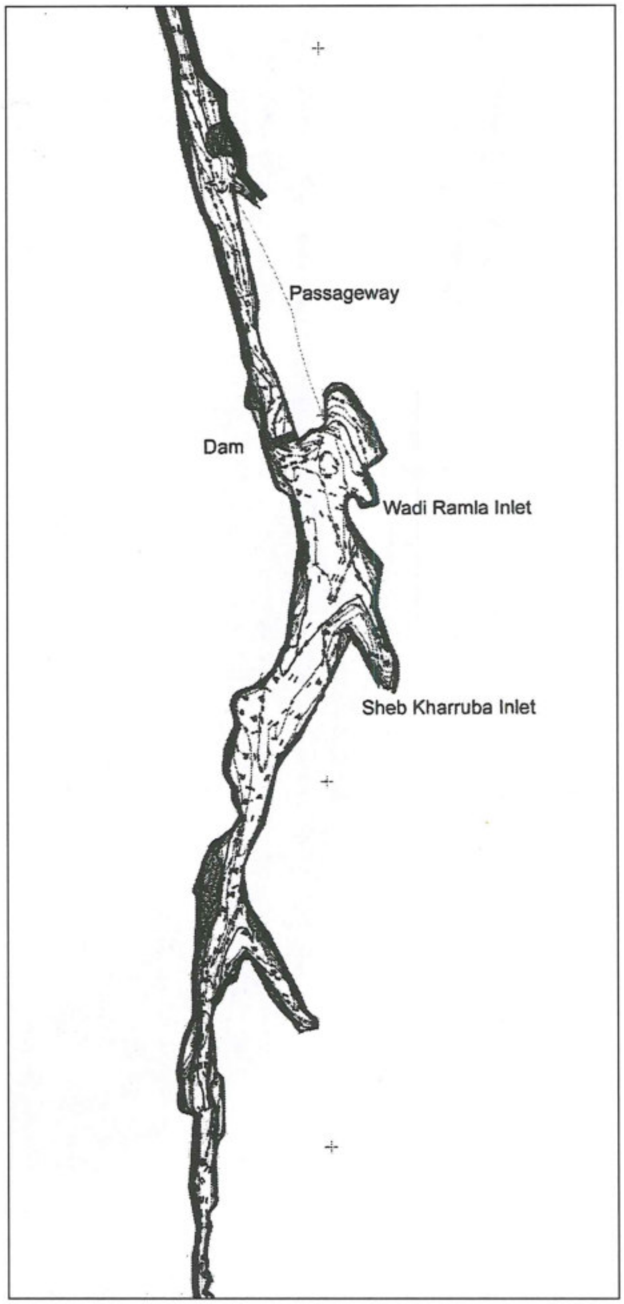
The technology used in the diversion tunnel of Sīq al-Mudhlim is very similar to the one used for the construction of the tunnel diverting the Orontes River around the port basin of Seleukia Piera, built during the reign of the Roman emperors Vespasian and his son Titus.

Sector MS 5

At the very bottom of sector 5, just before the narrow entrance to sector 6, eroded grooves in the bedrock on both banks of Wādī al-Mudhlim indicate that a dam was probably located here as part of the flash flood prevention system with parts of the grooves still visible in the bedrock. A natural crevasse behind the bedrock along the eastern bank of the gorge allowed an easy passage beside the dam. The basin of this dam took advantage of the extended width of the wadi bed upstream (**Fig. 10**). Additionally, the location of the dam allowed the detention of the runoff water from Sadd al-Kharrūba (سد الخروبة) and Wādī ar-Ramla (وادي الرملة).

Sectors MS 6 - MS 7, The Stilling Basin

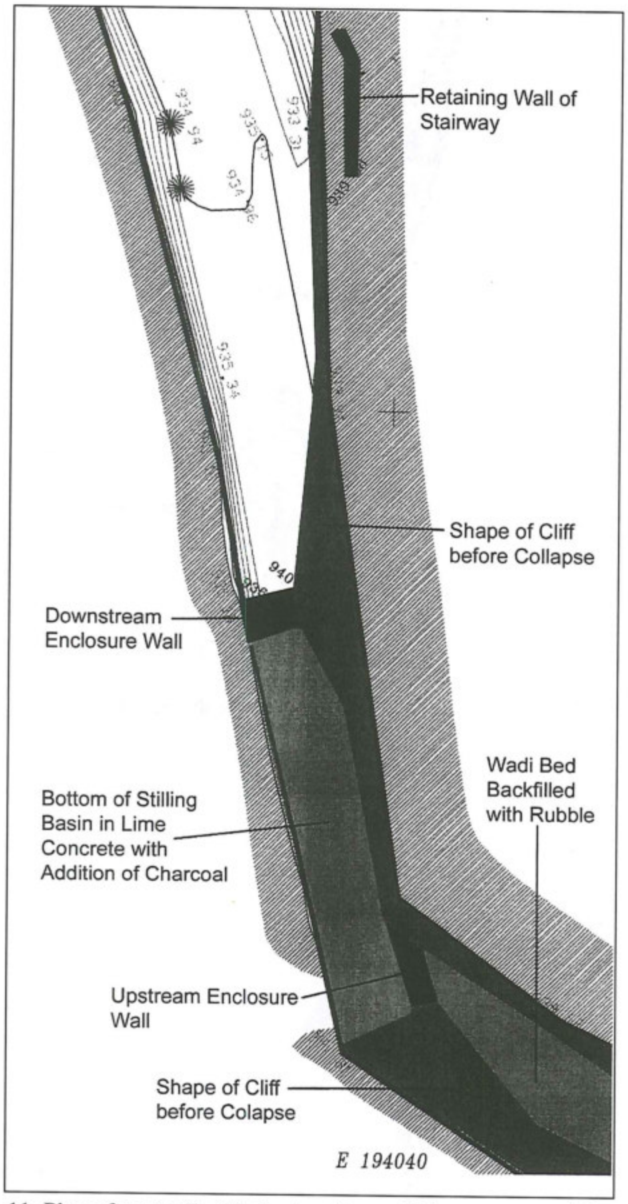
In the lower part of sector 6, there is a break in level of the bottom of the gorge of about 6m. At the lower end of this natural cascade are the ruins of what was once a closed basin. The basin has a slightly irregular rectangular shape due, no doubt, to the contours of the surrounding cliffs (**Fig. 11**). At its upstream end, the basin was entirely chiselled into the bedrock; only a short section on the eastern bank had to be closed by masonry. The downstream end of the basin was almost naturally closed by a rock projection in the eastern bank, therefore only a small, V-shaped dam had to be built for its complete closure (**Fig. 12**). Nowadays only a small fragment of the rock projection and most of the masonry has survived, because a great part of the bedrock has collapsed. To avoid scouring from the energy of the cascade, the bottom of the basin was completely constructed in lime concrete; its level was about one metre above the actual wadi bed. As there are no remains of any settlement activities or sanctuaries in the area, which could have required the storage of water, this hydraulic structure may be explained as a stilling basin, taming the speed and energy of the cascade.



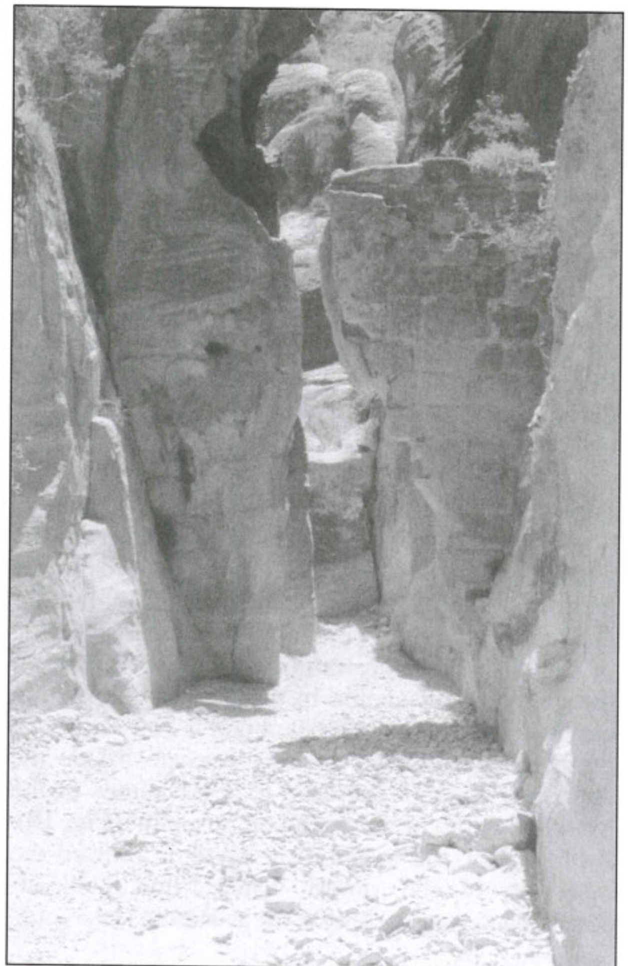
10. Plan of sector 5 showing the location of the dam and the passageway downstream of the inlets of Sadd al-Kharrūba and Wādī ar-Ramla.

Sectors MS 8 - MS 9, The Sanctuary

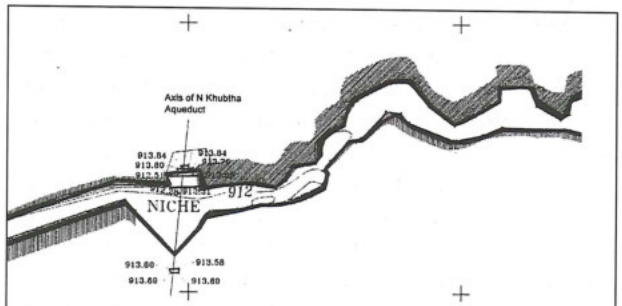
At the end of sector 7, Wādī al-Mudhlim joins Sadd al-Ma'jan (سد المعجن), and is forced to turn abruptly to the west at a right angle. Shortly ahead of the inlet into Wādī al-Maṭāḥa, the extremely narrow gorge of Sadd al-Ma'jan has a triangular widening in its southern cliff. Opposite this natural widening a deep and wide rectangular niche is carved into the bedrock (**Fig. 13**). The entire location is full of niches, some with Betyloi and others with various idols. The largest and most beautiful



11. Plan of sector 7 with the location and the remnants of the stilling basin.



12. The partially preserved downstream enclosure wall of the stilling basin on the right and the natural rock projection on the left; view upstream.



13. Plan of the sanctuary in Sadd Al Ma'jan showing the two most important niches and the superimposed axis of the northern al-Khubtha aqueduct.

is the niche in the artificial widening in the northern cliff, and is undoubtedly the most important sanctuary among the group of 90. The sheer number of niches and their concentration in such a restricted area makes it clear that this site had an outstanding religious character.

The survey of both banks above the sanctuary has confirmed a suggestion first made in 1970 by E. Gunsam (Gunsam 1983) that this impressive site must be seen in connection with the bridge of the northern Khubtha spring water supply system. The survey and detailed mapping of the area have now shown that the channel crossed the Sadd al-Ma'jan sanctuary on a semicircular arched bridge whose abutments are still recognizable. The bridge must have given the impression of a triumphal arch towering high above the access to this site of veneration. The close connection between sanctuaries and built elements of the Nabataean infrastructure has already been demonstrated by the excavations in the Sīq (Bellwald 2003).

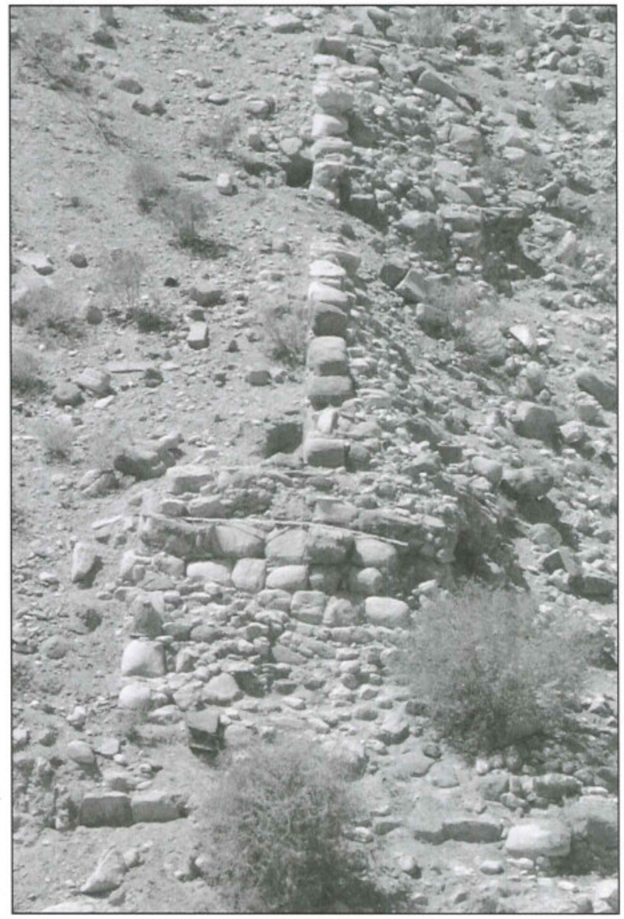
Starting from the outlet of Sadd al-Ma'jan into Wādī al-Maṭāḥa, the southern bank of the latter was completely reinforced by a retention wall in masonry of regular ashlar blocks, set up as headers and stretchers (**Fig. 14**). The survey has revealed that the reinforcement continues for the entire length of the shallow terrace to the south of Wādī al-Maṭāḥa down to the end of sector 11. Due to its steep and mostly rocky nature, the opposite northern bank of Wādī al-Maṭāḥa had no need of such protection.

Sectors MS 10-11, The Dams Protecting The City

In the middle of sector 10, a small side wadi enters Wādī al-Maṭāḥā from the north, descending from Mughur an-Naṣāra (مغر النصارى). Downstream from this inlet, the abutment of a large dam is visible in the debris of the northern bank of Wādī al-Maṭāḥa (**Fig. 15**). The dam continues to the north as a smaller wall. A water channel is attached to the western front of this wall. The construction of the conduit is 70cm wide and the channel itself is 20cm wide. On the southern bank, the abutment of the dam is visible too, but much less exposed. Even the water channel can be followed, and it is most probably the same conduit as the channel leading to or coming from the extended pool in front of the Carmine Tomb at the foot of Jabal al-Khubtha.

As mentioned above, the entire unstable southern bank of sectors 10 and 11 was fortified by a retention wall in ashlar masonry, of which long sections are still visible and others must be well preserved below the covering debris. In front of this wall the ruins of a cistern were found just upstream of the inlet of Wādī Umm Ṣayḥūn وادي ام صيحون (**Fig. 16**). The cistern is oriented parallel to the reinforcing wall and is 4.8m long and 2.6m deep. At its south-east corner the remains of a cylindrical feeding shaft are preserved. The interior surfaces of the cistern and the shaft still show the original hydraulic plaster. The bottom of the cistern is not exposed, but its level is most probably below the present wadi bed.

At the downstream end of sector 10, the bed of Wādī al-Maṭāḥa is lentiform. At both ends of this area, abutments of dams emerge from the debris of the northern bank (**Fig. 17**). There is an extensive



15. The dam below Mughur an-Naṣāra, view from the wadi bed towards the north. At the bottom, the full thickness of the dam, exceeding 6m, is visible. The narrow stone line above is part of the water channel which crossed Wādī al-Maṭāḥa on top of the dam.

14. The retention wall reinforcing the southern bank of Wādī al-Maṭāḥa at the outlet of Sadd al Ma'jan. The original masonry is visible on top of the restored foundation.

16. The ruins of the cistern opposite the inlet of Wādī Umm Ṣayḥūn. At the bottom right the cylindrical inlet shaft is visible.

17. The remains of the two dams at both ends of the lentiform section of Wādī al-Maṭāḥa at the downstream end of sector 10, view upstream.

fragment of the foundation of the upstream dam exposed in the middle of the wadi bed. Whereas the southern abutment of the upstream dam is recognizable in the debris along the southern bank, nothing from the downstream dam is exposed there.

Sector MS 12

The most impressive monuments in sector 12 are the ruins of the two bridges crossing Wādī al-Maṭāḥa from west to east. The remains of the larger bridge, which was used for carriages, are located about 150m upstream of the inlet of Wādī al-Maṭāḥa into Wādī Mūsā. The springers of the wide arches crossing Wādī al-Maṭāḥa are still well preserved in the northern abutment, whereas the constructions on the southern bank have been severely damaged by collapse. The foundation of the upstream face of this large bridge was protected by a dam with an original height of about 3m. Its lowest ranges of masonry are still preserved and have recently been restored.

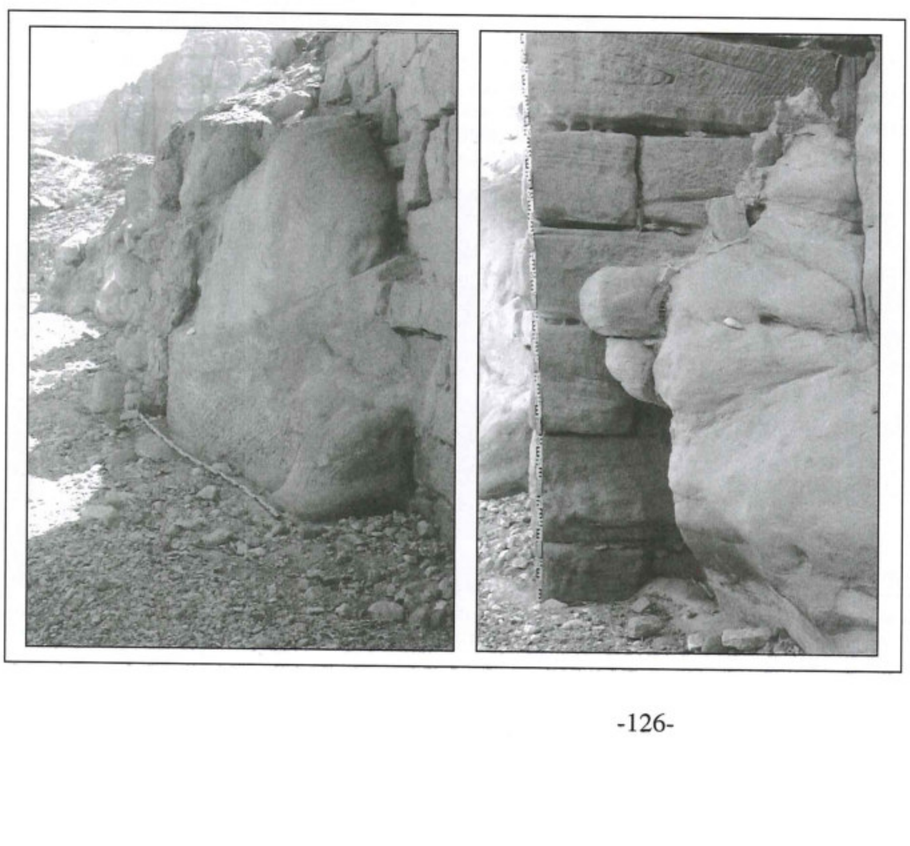
The ruin of the smaller, pedestrian, bridge is located about 90m upstream of the inlet of Wādī al-Maṭāḥa into Wādī Mūsā. As the bridge crossed Wādī al-Maṭāḥa at a lower level than the terraces on both banks, a staircase tower had to be built on the northern abutment. This tower is well preserved and forms a landmark in the urban pattern of Petra seen from the southern ridge of the city. In the wadi bed the foundations of this tower were protected by a reinforcing projection, built from very large blocks of limestone and sandstone (**Figs 18 and 19**).

A final dam crossed the bed of Wādī al-Maṭāḥa 40m from the inlet into Wādī Mūsā. Its groove in the bedrock of the northern cliff is well preserved, and some limestone blocks of impressive dimensions from the lower courses of the masonry still survive *in situ* (**Fig. 20**).

Conclusions

The Flash-Flood Detention System in Wādī Umm Ṣayḥūn

Strictly speaking,Wādī Umm Ṣayḥūn does not fall within the study area. Nevertheless, it is indispensable to include it for several reasons. First of all, apart from the diverted waters from the Wādī Mūsā,Wādī Umm Ṣayḥūn is the biggest inlet



18 – 19. Preserved fragments and the abutment carved into the bedrock for the re-inforcement protecting the protruding edge of the bridge for pedestrians.

20. The northern abutment of the lowest dam in Wādī al-Maṭāḥa, which prevented runoff water from damaging the northern Nymphaeum. These fragments are now no longer visible, as they have been hidden behind a protecting wall built by the DoA in the summer of 2002.

into Wādī al-Maṭāḥa . Secondly, Wādī Umm Ṣayḥūn has cut down deeply into high and extended mounds of sand eroded from the surrounding hills, making its banks very unstable. There is therefore the possibility of massive erosion of the banks that would choke Wādī al-Ma āḥa.

To address this danger the Nabataeans reinforced the banks of Wādī Umm Ṣayḥūn with enormous retaining walls of ashlar blocks. These walls were parallel and effectively canalized the wadi bed over a length of about 200m and a width of 20.7m. In the upper part of Wādī Umm Ṣayḥūn, where several smaller inlets join it, the retaining walls bow out into a cylindrical shape (**Fig. 21**), and in the centre of the wadi at this point is a square structure of unknown function.

130m upstream of its outlet into Wādī al-Maṭāḥa, the retaining walls canalizing the runoff water from Wādī Umm Ṣayḥūn end in a massive dam structure, closing the wadi like a valve. The dam structure is very like the dam closing the basin in front of the entrance to the Sīq and might well also have carried a bridge. On its eastern abutment the foundations of a rectangular building of 14.8 by 11.75m may still be seen, with walls 2.82m wide (**Fig. 22**). Access to the building was from the north and the door jams are still *in situ*.

21. The exposed sections of the western half of the cylindrical structure at the upstream end of the retaining walls in Wādī Umm Ṣayḥūn.

The Flash-Flood Diversion and Prevention System in Sīq al-Mudhlim and Wādī al-Maṭāḥa

The archaeological survey has shown that the area under study was an integral part of the flash flood prevention system built together with the infrastructure in the Sīq . Without the diversion of the runoff water from upper Wādī Mūsā through the tunnel into Sīq al-Mudhlim, Sadd al-Ma'jan and Wādī al-Maṭāḥa, the paved street and the spring water supply system in the Sīq would not have survived the impact of any severe flash flood. The preliminary evaluation of the results of the archaeological survey highlight how efficiently the Nabataean flash flood protection system took advantage of natural conditions and how it was integrated into the urban pattern of the then newly built city.

From the arched culvert in front of the Mövenpick Hotel down to the Obelisk Tomb, Wādī Mūsā passes through a necropolis, most of which is preserved and still visible on the southern bank. Of the monuments on the northern bank only the tomb (No. 4) near the Guest House and a much eroded structure opposite the Obelisk Tomb are preserved; and now the cistern that has been discovered can be added. The descriptions above of the cistern on the northern bank and the tombs and sanctuaries on the southern bank have shown that all these monuments were oriented towards a wadi bottom much lower

22. The dam structure at the outlet of the canalized section of Wādī Umm Ṣayḥūn, view from upstream in the direction of Wādī al-Maṭāḥa and the Palace Tomb. The rectangular building was erected on the left section of the dam structure.

than today's level, otherwise they would have been threatened by periodic inundation. Patches of the bedrock occasionally exposed in the wadi bed after flash floods lead to the conclusion that in the Nabataean period the wadi bottom was kept clean and the bedrock was exposed throughout this entire section. To avoid any deposition of debris, a continuous and free discharge of the runoff water had to be assured; therefore, no water detention structure was ever built in this area.

The extended area at the bottom of sector 3, where the course of the wadi bends to the north, was completely remodelled as an enormous basin. The northern bank of this basin was reinforced by the dam supporting the high level road. Opposite the Sīq entrance, this dam crossed the bed of the Wādī Mūsā, reducing the outlet of the basin to the width of the tunnel and thus the discharge from the basin was restricted to the capacity of the tunnel. The survey has further revealed that the bottom of the basin was considerably lower than its outlet, hence boulders or trees were held back in order to prevent them from obstructing the outflow through the tunnel.

From the outlet of the basin in front of the Sīq entrance to the end of sector 5, the outflow of flood water was not detained so as to prevent any backwater towards the tunnel. At the bottom of sector 5 Sīq al-Mudhlim widens out. In this same area, two additional side wadis, Sadd al-Kharrūba and Wādī ar-Ramla, bring in runoff water into the main gorge. The favourable conditions of the topography in this location were used for the creation of another detention basin, which had a backwater height of at least 3m. The location of the basin was also acceptable because a natural path circumvents the dam on a terrace along the eastern bank, without which maintenance downstream would have been obstructed.

The extremely narrow passage along sectors 6-7 did not allow any construction of detention dams. The velocity and thus the pressure of the water against any dams would have led to their immediate collapse as was demonstrated by the immediate destruction of the gabions built by the DoA and UNESCO in this location in 1996. The only element detected was a stilling basin in the lower part of sector 6, built to still the discharge of a natural cascade with a height of about 6m. To avoid scouring, its bottom was filled with a thick layer of lime concrete. With this small construction, the devastating effect of the natural cascade was considerably reduced.

At the outlet of Sadd al-Ma'jan, an important sanctuary was situated directly below the bridge of the northern al-Khubtha spring water supply conduit. Among all the sites of veneration in Petra which were linked with the outstanding importance of water for daily life, this sanctuary, with the towering bridge like a triumphal arch high above, must have been by far the most impressive.

At the inlet of Sadd al-Ma'jan into main Wādī al-Maṭāḥa, the diverted flood water meets with the runoff water from upper Wādī al-Maṭāḥa, descending from the northeast. To protect the protruding southern bank of Wādī al-Maṭāḥa from erosion, a reinforcing wall was built from the inlet of Sadd al-Ma'jan down to sector 11. The construction of this retaining wall of ashlar masonry, with headers and stretchers, was the only intervention undertaken to tame the flood water. To avoid water backing up into Sadd al-Ma'jan, no detention structures were built. In the middle of sector 10, Wādī al-Maṭāḥa leaves the area of the necropolis and enters the city. From this point down to the inlet into Wādī Mūsā near the northern Nymphaeum a close sequence of dams was built in order to detain the flood water and to slow it down. An important one was built at the entrance of Wādī al-Maṭāḥa into the city area, immediately below the inlet descending from Mughur an-Naṣāra and at a short distance upstream of the inlet of Wādī Umm Ṣayḥūn. This dam was obviously built for two purposes: firstly it had to detain the flood water from the east in order to avoid damage to structures in the city and secondly it had to ensure the unobstructed inflow of the runoff water from the north descending from Wādī Umm Ṣayḥūn. The two dams at the downstream exit of sector 11 held back the runoff water from the inlet of Wādī Umm Ṣayḥūn. The dams in sector 12 were of much smaller dimensions and were built to protect the foundations of the two bridges. The lowest dam, some metres upstream of the inlet of Wādī al-Maṭāḥa into main Wādī Mūsā, was the last detention structure, which would have avoided water backing up in the direction of the theatre area and any inundation of the area around the Nymphaeum, which forms part of the city's spring-water supply system.

Hydraulic and Hydrologic Study

The Nabataeans had a variety of techniques to avoid flood damage and implemented them according to the particular requirements of each location. The following methods are known to have been used:

- Reduction of peak flow by building reservoirs.
- Confinement of the flow within a predetermined channel by levees, floodwalls or a closed conduit.
- Reduction of peak stage by increased velocities resulting from channel improvement.

- Diversion of floodwaters through a flood bypass, which may return the water to the same channel at a point downstream or deliver it to another channel or different watershed.
- Flood plain management.

This part of the project set out to understand the hydrology of the study area and based on that understanding, to make recommendations for certain flood protection measures. Flood protection structures require planning and engineering design. Every installation performs an operative function determined by hydrology and hydraulics, and a load-carrying function determined by structural considerations and construction procedures. In addition there are certain constraints imposed when working in an archaeological site.

The design, therefore, involves two independent design problems: hydraulic design and structural design. The intention of the hydraulic design is to determine the most economic installation by realistically anticipating the effects of hydrology in establishing satisfactory hydraulic operation. The intention of the structural design is to ensure the construction of an installation with sufficient strength to support the loads without adversely affecting the environment of the site.

A dam should be placed so as to achieve maximum protection, utility and safety and its design is, of course, greatly influenced by location and site conditions. Care must be taken to avoid introducing objectionable secondary effects or interfering with desirable hydraulic operating characteristics. The dam sill length should be designed to discharge the design flow with a reasonable head water level. Proper measures must be provided at the outlet, such as cascade-shaped dams, to prevent the downstream erosion of the bed, the banks and undercutting of the dam toe. The dams proposed for sectors MS5 and MS11 were designed with all the above constraints considered (see below).

Data Collection and Review

The data collected for the project included the topographical maps, climatic parameters and rainfall intensity records for rainfall stations at and near the study area, notes and photographs from site visits, the field surveys results, the geological and geo-technical investigations and relevant previous studies such as Petra Flood Protection by Dar Al-Handassah and Protection of the Sīq area by the PNT consultants MeeM.

Data were also made available by the Ministry of Water and Irrigation, the Department of Meteorology, the Royal Geographic Centre and the Natural Resources Authority.

Rainfall data of daily and monthly records for the Petra (1962-2001), aṭ-Ṭayyba (1962-2001) and Wādī Mūsā rainfall stations (1937-2001) were used to draw some statistical figures. The long annual rainfall averages for the three stations are 110.9mm, 164.4mm and 171.5mm respectively. The maximum average monthly rainfall falls in December for Petra and January for the Wādī Mūsā and aṭ-Ṭayyba rainfall station.

Site Investigation

The preliminary examination of the hydrology in the area was carried out based on site inspection. This was done to qualify both the quantity and distribution of surface water originating from the catchment areas of the natural drainage for Wādī Mūsā and Wādī al-Mudhlim. As with the archaeological study, the site investigation focused on the areas of the Wādī Mūsā beginning at the recently reconstructed new Zurrāba box culvert, 650m to the east of Mövenpick Hotel, through the tunnel and along the entire Wādī al-Mudhlim and finally along the Wādī al-Maṭāḥa as far as its inlet into Wādī Mūsā, including all tributaries (**Fig. 2**).

The following information was gathered:

- Runoff coefficients of different parts of the catchments.
- Potential sites for generating flood flows.
- Sites for proposed flood protection structures.
- Flood marks required to estimate flows.
- Characteristics of flow sections, such as roughness, sedimentation problems and erosion due to human activities.

Travelling from the Zurrāba box culvert (sector MS1) down through each sector, the main features were as follows:

Sector MS1 and MS2

In these two sectors, wadi training for flow modification purposes was carried out (in 1998 by the Department of Antiquities) and some sidewalls were constructed to enhance the landscape without considering the hydraulic characteristics of the wadi. At the beginning of sector MS1, a box culvert was built recently, that could have adverse effects on the main hydraulics of Wādī Mūsā. Another arched culvert in front of the Mövenpick Hotel was built (without alignment) following the main wadi flow.

Sector MS3

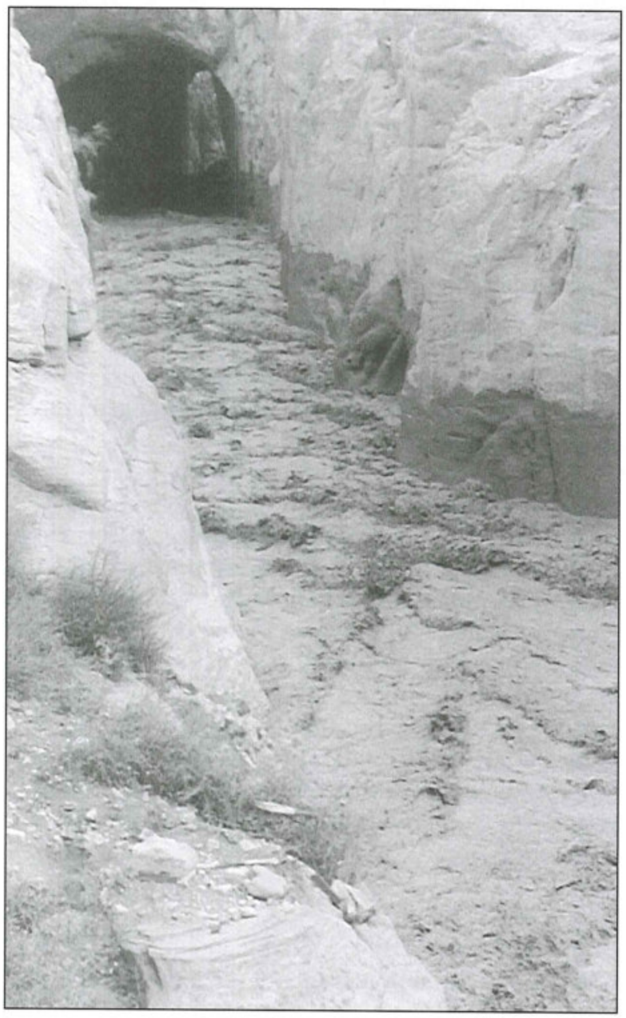
In sector MS3 the wadi meanders. There is a box culvert and a potential site for a flash flood detention basin at the end of the sector. The detention basin could cover the entire curve, in which the direction of the Wādī Mūsā flow changes from east-west to north-south. This is the location of a Nabataean basin that was designed for the same purpose (**Fig. 5**). Such a basin could hold back a large quantity of the flood flow and reduce the peak. The Sīq entrance box culvert and the channel at the upstream end of the tunnel are also in this sector. The low height of the box culvert leads to a blockage problem after floods and as is not aligned with the channel leading into the tunnel, cross-waves are caused, even at low flow levels (**Fig. 23**).

Sector MS4

Hydraulic analysis was carried out for the tunnel in this sector to check for its capacity and performance during flood conditions. This was essential in order to resolve the stability problems of the entrance to the tunnel.

Sector MS5 and MS6

At the end of sector MS5, Wādī al-Mudhlim widens sufficiently to create a suitable area for a reservoir and the Nabataeans had used the area as such. Due to the favourable conditions of the topography, the reservoir could be designed to be large enough to detain the flood flow, which would considerably reduce the flow peak.



23. Cross-waves at the entrance of the tunnel.

The end of sector MS6 is rather narrow, with possible high flow velocity if there is no dam and reservoir. From this section downstream to the end of Wādī al-Mudhlim, any protective structure is not recommended due to high flow velocity and insufficiently stable section. This was proven by the immediate destruction of some gabions built by DoA and UNESCO in 1996.

Sector MS9 to MS11

At the outlet of Wādī al-Mudhlim into Wādī al-Maṭāḥa, the diverted floodwater meets the runoff water from upper Wādī al-Maṭāḥa, coming from the north-east. At the end of sector MS9, a potential site for a detention reservoir could exist. All dams in Wādī al-Maṭāḥa can be expected to be long, with low crest levels due to the wide and shallow wadi section. In the middle of sector MS11, a small side wadi enters Wādī al-Maṭāḥa from the north. Just before the inlet, part of a large dam is visible in the debris, as described in the archaeology section above. The dam is long and low but could create a large reservoir due to the flat topography that would allow a large surface area in a shallow reservoir.

Sector MS12

The numerous monuments and ruins in the upstream part of this sector need protective work and the outlet of Wādī al-Maṭāḥa into Wādī Mūsā needs to be protected against flooding. There are two potential sites for dams, at the beginning and the middle of the sector. The reservoirs created could detain the floodwater and protect this rich archaeological site and junction point with Wādī Mūsā. Since the two wadis meet at an almost 90o angle, even with a moderate peak floodwater hits the south bank of Wādī Mūsā and floods the area.

Hydrological and Hydraulic Analysis

Flood Mitigation Measures

Wādī al-Mudhlim carries high flood flow because of the Wādī Mūsā flood diversion into it through the tunnel. The high flood flow is characterized by short duration and high peak even with low rainfall intensity, and heavy sediment loads. The short duration is characteristic of the catchment and is a result of the number of streams (in this case, four) and steep slopes. The flood peak is mainly controlled by the catchment surface characteristics, which here are a high runoff coefficient and curve number, causing the surface to have both a high runoff and low losses. The sediments can be attributed to the nature of the surface materials of the catchment surface and in particular the erosion of the sandstone rocks.

The detailed investigation carried out on the hydrologic and hydraulic conditions allowed certain recommendations to be made, although further geotechnical investigations are still needed in order to estimate the rock conditions and the sediment bed thickness. Four important measures were thus proposed to establish a flood mitigation system that would achieve considerable safety:

- Enhancing the tunnel bed condition by clearing the fallen rocks, thereby improving the flow capacity of the tunnel and decreasing the water depth inside.
- Three check dams before the diversion at the Sīq entrance in order to stop sediment movement, specifically the bed load.
- A large capacity detention basin at the site between the check dams and the Sīq entrance to decrease the flood peak before the tunnel.
- Two main dams in sectors MS5 and MS11 to increase the detention time and to lower the flood peak downstream of the Wādī al-Mudhlim.

Sīq al-Mudhlim Tunnel

Flow through the tunnel was investigated in detail and revealed a very critical condition. The geological study showed a delicate situation regarding falling rocks from the tunnel ceiling (See below). Some blocks had fallen in December 2000 and it was essential to clear the tunnel bed to smooth flood flow through the tunnel and enhance its flow capacity by reducing the roughness coefficient. The roughness coefficient is inversely proportional to the flow capacity.

Therefore, over two months, from September to November 2003, these fallen rocks were cleared by TarMeeM International on contract to the Petra National Trust and in co-operation with the Department of Antiquities. The area cleared stretched over 160m from the box culvert at the entrance to the Sīq , through to the far end of the tunnel. Temporary ramps were set up for safe access to and from the tunnel, which were dismantled on completion of the project.

All the boulders in the tunnel were crushed manually, using such hand tools as chisels and hammers to avoid any vibration in the delicate tunnel walls. Crushed boulders and much washed-in sedimentation were removed from the entire tunnel bed. A small amount of sediments were left against the tunnel walls to act as a buffer between them and flood water.

How the tunnel looked before and after the clearance is shown in **Figs. 24 and 25**.

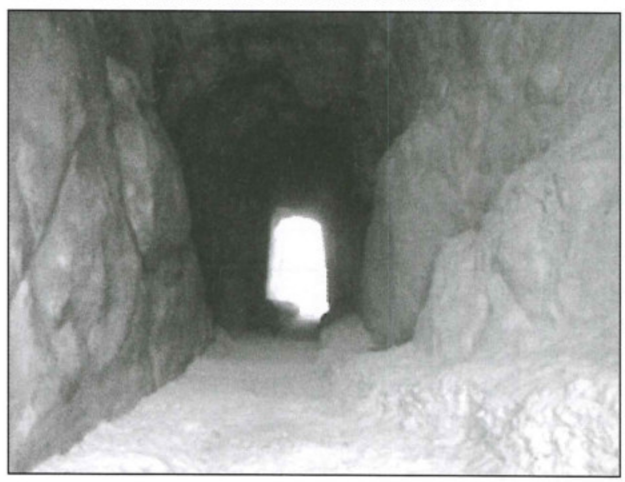
The increased flow capacity that the clearance has allowed should reduce the flood level inside the tunnel and this in turn should reduce the chances of collapse of the tunnel sides and therefore also of the ceiling, thereby reducing the likelihood of rocks falling in the future. (See geological section, below.)

Proposed Structures

Check Dams

Three check dams were proposed in Sector MS1 between the two culverts of Wādī Mūsā and the Mövenpick Hotel. These check dams are planned to be100m apart and 1m high with an upstream and downstream slope of 1 vertical to 5 horizontal and a dam crest width of 1m. They are intended to stop the sediment bed load moving from Wādī Mūsā through the tunnel to the Wādī al-Mudhlim. Sediment accumulation could flatten the

24. Tunnel entrance before clearance of rock fall.



25. Tunnel entrance after clearance of rock fall.

wadi bed slope, which would lead to better flow conditions in the future.

Detention Basin

A basin on the bend of the Wādī Mūsā, just before the tunnel was proposed to hold back the flood peak before flowing through the existing box culvert and on into the Sīq al-Mudhlim tunnel (as the Nabataeans had done, see above). According to the studies, the positive effect of such a basin on the tunnel section regarding the flow depth and velocity is high at a 2-year return period and still considerable at a 5-year return period, with lower effects on the longer return periods. The study considered the effect of peak flow and not other flows and a basin would change the flow hydrograph and reduce the flood impact on the tunnel (**Fig. 26**)

The basin was proposed to have a maximum depth of 5m, based on stability and safety measures. The side slope was planned for 1:1 and would need geotechnical approval for stability. It is designed to absorb the flood peak and increase the detention time as a necessary measure for emergency evacuation.

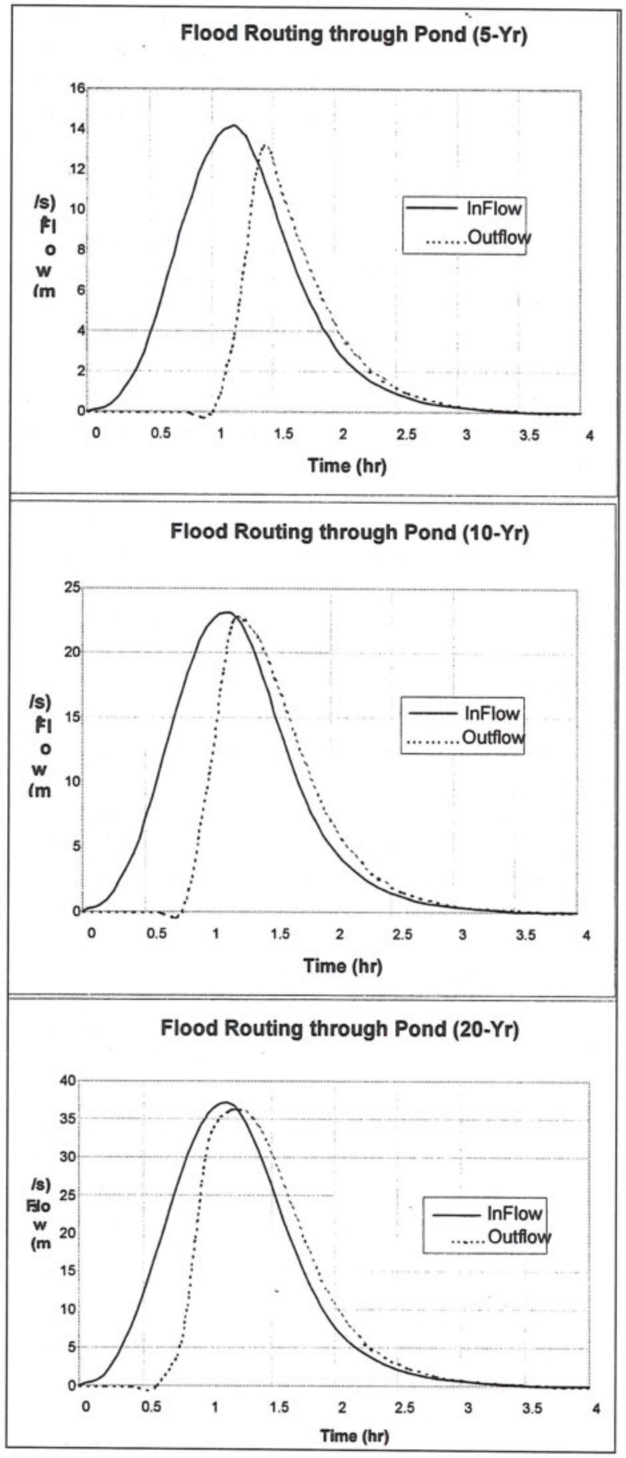
However, the design of the basin can vary to take into consideration floods at reasonable return periods (100-yr or more) and also depending on the surface area, required depth and function required of the basin as a sediment trap to detain large boulders, preventing them from entering the tunnel just downstream. The basin could be extended more if the entrance to the Sīq were to be restored based on the results of the archaeological investigations.

Two Main Dams

The study showed that there are two appropriate potential sites for dams with small reservoirs behind. The first site, located at the end of Sector MS5, is a promising location for Dam 1. The second site is situated in Sector MS11 with a larger reservoir area and higher capacity. **Table 1** summarizes the main features of both dams, which indicates a lower dam section for Dam 2 with comparable capacities.

Table 1: Main Features of Two Main Dams.

Feature	Dam # 1	Dam # 2
Bed Level (masl)	954.50	883.50
Crest Level (masl)	959.00	887.00
Dam Height (m)	4.50	3.50
Flood Top Level (masl)	961.00	889.00
Crest Length (m)	13.20	11.50
Reservoir Capacity (m^3)	3128.80	2514.50
Top Reservoir Area (m^2)	2483.20	2282.30



26. Flood flow through the basin.

The dams were designed to suit the archaeological site and to fit the geological conditions. The major constraint is the stability criteria, which makes a cascade section a reasonable option. A cascade section was thus designed, creating a stable structure on both upstream and downstream sides. The dam crest is 1m wide with 2 horizontal to 1 vertical side slopes (**Fig. 27**). The side slopes consist of steps 1m wide and 0.5m high. The weight of water on the cascade upstream increases the stability and the cascade downstream discharges the flood with dissipating energy.

Conclusions

The study showed that the area was an integral part of the flood protection system built by the Nabataeans together with the infrastructure in the Sīq . The diversion of the runoff water from upper Wādī Mūsā through the tunnel into Wādī al-Mudhlim and Wādī al-Maṭāḥa was essential to protect the paved street and the spring water supply system in the Sīq .

Today an advanced and integrated flood protection system could exist, using this detailed hydrologic and hydraulic study, for diverting all Wādī Mūsā floodwater away from the Sīq efficiently and safely using local materials at appropriate sites. The points below highlight the type of problems that will face Wādī al-Mudhlim in the absence of the proposed management:

- Continued earth removal from just downstream of the arched culvert near the Mövenpick Hotel will result in the downstream blocking of the existing culvert and damage to the tunnel along with many of the archaeological remains.
- Figure 28 shows significant erosion of the foundations of sidewalls, which could lead to a failure. This risk can be reduced dramatically if the present management plan is executed.
- Another example is the erosion of wall foundations and gabion failure along the wadi in different sectors.
- The sediments are another hazard along the wadi, which can act as an erosion machine driven by the flood flow.
- Future activities can easily be damaged if there is no flood management plan for Wādī al-Mudhlim.
- The exit flood, where the Wādī al-Maṭāḥa rejoins the Wādī Mūsā at the Nymphaeum, could damage very important archaeological remains if there is no management.

Geological Study

Introduction

A detailed study of the geology of the project area was carried out and particular attention was devoted to the tunnel (Sīq al-Mudhlim). The lithological and physical properties of the rocks were identified, with an emphasis on recording the faults, joints and cracks in the hard rocks along Wādī al-Mudhlim and the tunnel. The condition of the bedrock in the tunnel was assessed by identifying why there have been collapses of its ceiling in the past and any physical indicators of possible future collapses.

There had been a collapse of the ceiling in December 2000 and its impact (or that of any other potential collapse) on the flow of the water in the tunnel and on the downstream area was studied, along with measures for the clearance of recent collapse (see above).

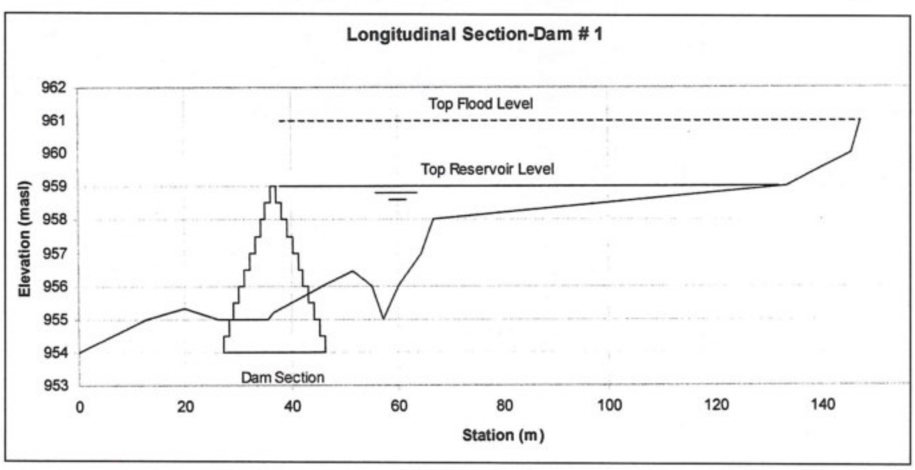
The Regional Geological Setting

The regional geology of the Wādī Mūsā area has been published elsewhere and will not be detailed here, however it is important to remember how much the local rocks have been influenced by the Jordan Rift Valley and the Dead Sea faulting. Petra and its surroundings are thus characterized by a system of faults and cracks.

The stratigraphic series used here was constructed using terminology adapted by the Jordan Mapping project (N.R.A.) and this terminology was further simplified using colour as it is the most distinguishing feature.

Stratigraphy

The lithological units outcrop because of the



27. Longitudinal section of Dam 1.

steep terrain, while the wadi and gorge bottoms are covered by Quaternary deposits and the high flat areas are masked with a thin cover of sandy soil.

The sequence in the study area is as follows (from the oldest to the youngest):

- *Cambrian Sandstone (Umm Ishrin formation or Red Brown Sandstone)*

Overlaying the quartz porphyry (Bayda Porphyry Unit), the contact is well defined to the west of Petra along Wādī Mūsā (especially west of ad-Dayr area), where the wadi cuts deeply into the rock, forming gorges.

The lower portion (12m thick) of this unit is composed of a sequence of fluviatile, coarse to pebbly sandstone and cross beds are formed in several layers each from 70cm to 150cm thick.

The rest of the Cambrian sandstone (310m thick) consists of many layers of coarse grained, cross bedded sandstone containing pebbles of quartz, generally of dark red-brown colour and in some parts they are intercalated with micaceous silty sandstone layers. This rock unit outcrops along the west side of Wādī al-Mudhlim and is strong because it is well-cemented.

- *Ordovician Sandstone (Disi formation or White Sandstone)*

This unit lies unconformably over the Cambrian sandstone, with a thickness of 70m exposed, consisting of cross bedded sandstone with distinct jointing. It is characterized by its white colour, spheroidal dome-shaped weathering, and its strength is medium to low due to poor cementation. It outcrops clearly on the eastern side of Wādī al-Mudhlim.

- *Wadi Bed Material (Wādī al-Mudhlim)*

The thick layer of wadi deposits hides ancient alluvial deposits of a few metres thick. On both flanks of the wadi, these deposits are well cemented and assume the nature of a conglomerate. In the wadi bottom, recent unconsolidated, heterogeneous alluvial deposits are present, varying in thickness between 4-8m and are composed of silt, chert, limestone pebbles, boulders and gravels of different sizes.

Summary of Findings

Fractures and Discontinuities

Fracturing of rock is one of the most important implications of faulting within the area, especially where the wadi course follows the fault line. Fault lines are an easy course for floodwater to follow since the rock is very weak because it does not form a continuous solid stratum.

A cross-section along Wādī al-Mudhlim shows different types and sizes of discontinuity. The joints, fractures and cracks were measured in order to carry out statistical analysis and evaluation. The size, extension, opening and filling materials of these fractures were also considered during the evaluation of the stability, in addition to their strike and dip measurements.

Weathering Effects

The superficial weathering penetrates only to shallow depths in the sandstone. The main factors that cause the weathering are wind and water.

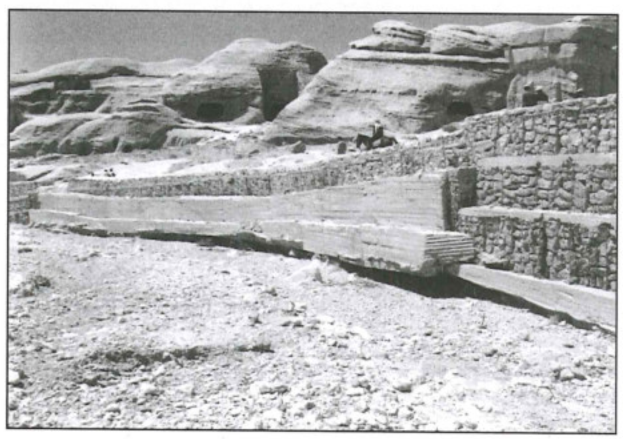
The effect of wind was noted in the naturally exposed rock mass within and around the site area; the impact of wind is higher on the white sandstone where the shape of the rock mass is rounded and the surface is smooth.

Water plays a greater role in the weathering process: the action of water starts by dissolving the cement in between the sandstone grains, the dissolved material accumulates in the form of salts on the rock faces, and eventually this salty layer collapses. Also water percolation along discontinuities leads to the opening of fracture planes and degradation of the exposed rock surfaces.

During floods the action of water increases by means of erosion of the rock faces due to the high energy of the water, in addition to the effect of the bed load where the gravel and boulders repeatedly hit the bedrock surfaces.

Failures

A large number of failures was noted in the area adjacent to the Wādī al-Mudhlim, which are in general related to natural processes such as water action, especially in the tunnel area. These features will be discussed below.



28. Erosion cavity below the foundations of the sidewalls of Wādī Mūsā, in the Bab as-Sīq area.

Geology of Sīq al-Mudhlim, the Tunnel Area

Wādī Mūsā is the main wadi in the site area, trending E-W with subsidiary wadis branching in all directions within the catchment area of the Wādī Mūsā basin. Wādī Mūsā developed by cutting through weak zones, mostly main faults and master joints, which include the Sīq. The water was diverted by the Nabataeans away from the Sīq , through the tunnel to follow the Wādī al-Mudhlim fault. Subsidiary wadis also often follow such joints.

Wādī al-Mudhlim itself is a major normal fault where the white sandstone rests against the red brown sandstone. This fault is a set of parallel fault planes having the same trend and approximately the same dip. The tunnel was excavated along the main fault plane.

The tunnel is about 9m high, 6m wide and 83m long. The wadi bottom is completely covered by recent deposits. At the outlet of the tunnel the energy of the water flow during flood periods has eroded more than 1.5m of the wadi deposits in the central portion. Similar situations were observed inside the tunnel (before its recent clearance) with an even greater degree of erosion.

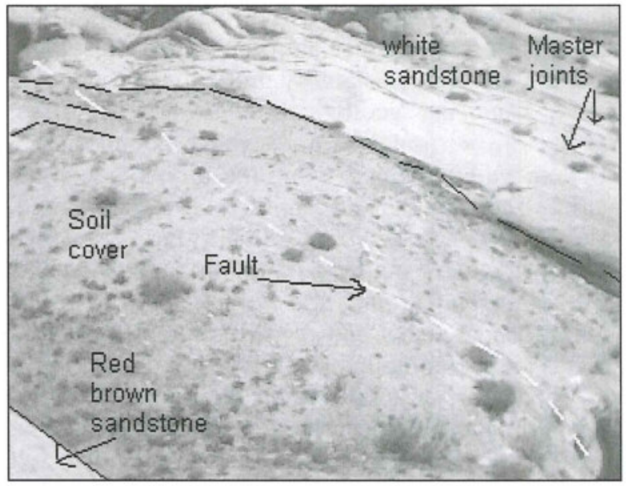
Except for the recent wadi deposits only two units (described above) outcrop within the study area, the white sandstone and the red brown sandstone.

East of the wadi generally, the white sandstone is exposed. It weathers into spheroidal shapes, has distinct master joints and some of these joints have been eroded forming subsidiary wadis. The flat areas are covered by sandy soil. West of Wādī al-Mudhlim, the red brown sandstone outcrops with clear cross bedding; it is much stronger than the white sandstone.

The top of the tunnel is a flat area covered with sandy soil (**Fig. 29**) where the fault traces are partially covered. The weathering effects are very distinctive in the northern portion. East of the tunnel the white sandstone is exposed with a smooth weathered surface and there are a number of master joints running parallel to the main fault. These joints have openings ranging between 1 to 3cm, filled partially with calcite and sand, while the joints observed west of the fault are filled with sandstone pieces, which are more resistant to weathering than the rock masses.

Two main sets of joints have been observed, one is almost perpendicular and the second parallel to the fault. The joint planes form a suitable environment for plants to grow as their roots can penetrate easily.

In the northern portion of the top of the tunnel



29. Top of the tunnel area.

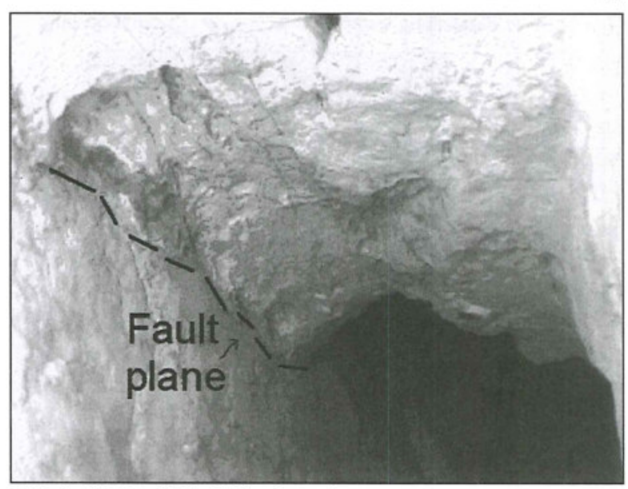
the soil cover is limited to the low areas and the fault plane can be clearly observed crossing through the rock units.

One of the most important structural features that has an impact on the tunnel is the Wādī al-Mudhlim fault, along the plane of which the tunnel was excavated (see above). This fault can be traced along the wadi 150m south of the Sīq , along the tunnel and along the wadi as far as the north-eastern corner of Jabal al-Khubtha. The Wādī al-Mudhlim fault is considered a normal fault, where the ar-Ramla block has moved downwards relative to the al-Khubtha block. Its strike is within the range of 355 to 10o from the north and the dip varies from 75 to 85o. From the horizontal, it dips toward the ESE.

Inside the tunnel, the fault plane has a smooth planer surface (**Fig. 30**), and five sets of joints were recorded in the ceiling of the tunnel.

Stability of the Tunnel

The rock thickness above the tunnel ceiling



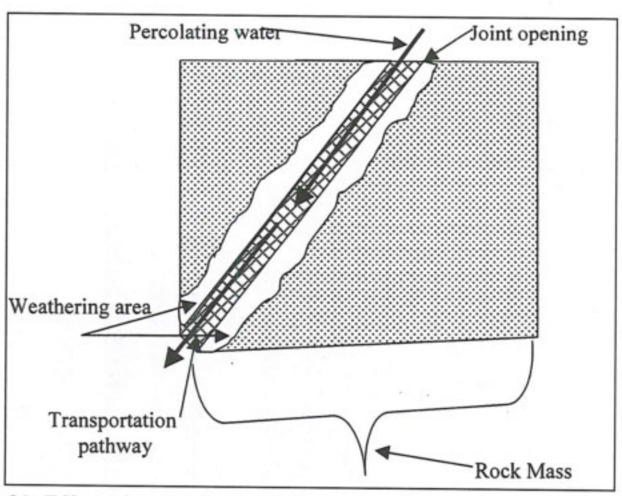
30. The Wādī al-Mudhlim fault plane.

ranges from 4-7m, which is a very low load and has therefore no significant effect upon the failure process. Instead the stability problems of the tunnel come from the geological conditions of rocks, where the surrounding rock mass is intensively jointed. Falls of blocks from the tunnel side walls and ceiling are the only failures so far recorded. These are structurally controlled failures governed by the geometry of the tunnel, structural elements present in and around the tunnel, the geological conditions of rocks and the effects of water from floods and percolation.

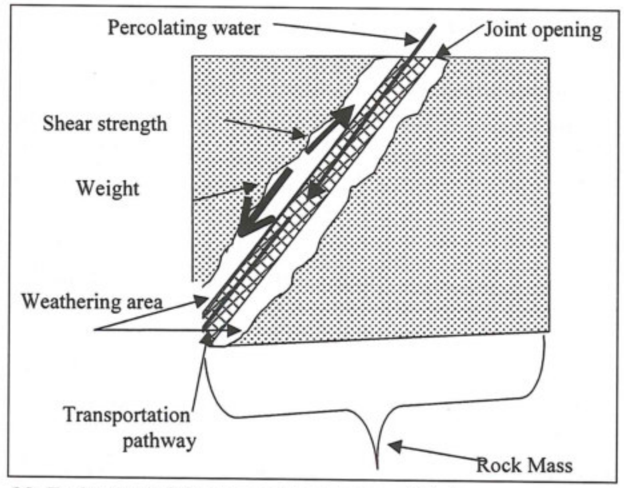
The tunnel was excavated along the Wādī al-Mudhlim fault (as described in the archaeological section above), so that its west wall and the fault have the same trend. The fault generated a number of joint sets, the most important of which are the two sets parallel to the fault trend and therefore to the wall of the tunnel. These are extension joints, mostly open; one set has the same direction of dip as the fault plane, while the other dips in the opposite direction. Within the tunnel area these two sets have spacings of less than 1m and openings of 2-3cm.

The joint planes are distinct in the wall of the tunnel and the dip of the joint sets ranges between 75 to 80o, which is greater than the friction angle of this plane in any case. Water percolating through the joint sets and fault plane has the following major effects:

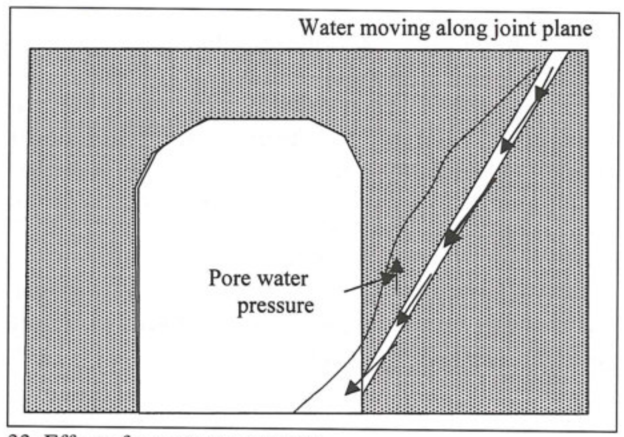
- Weathering along the joint planes and transport away of the material from the rock masses and from the filling of the joint openings (**Fig. 31**).
- Reduction of the shear strength of the joint planes (**Fig. 32**).
- Increase of the pore water pressure (water head above the joint plane) creating a force acting upwards (**Fig. 33**).



31. Effect of percolating water.



32. Reduction of the shear strength along joints.



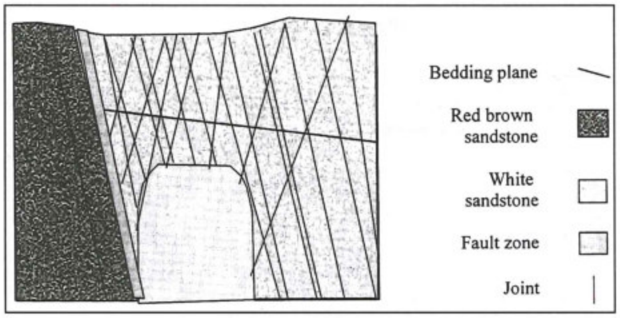
33. Effect of pore water pressure.

- Saturation of the rock mass by filling the space between the sand grains with water, creating extra weight.
- Widening of the joints planes and release of the blocks from the surrounding rock mass.

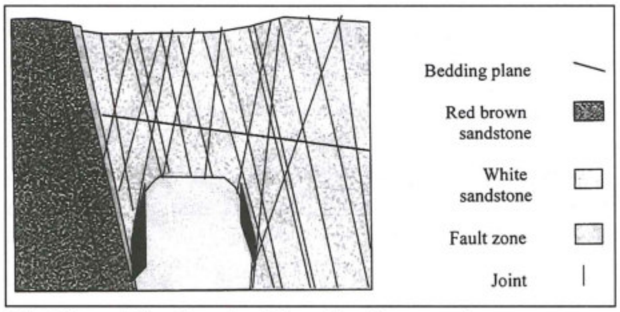
The conditions just mentioned are ideal for the sliding and free fall of blocks.

The two joint sets, the fault plane and the bedding planes all influence the stability of the tunnel ceiling and side walls. Taking into consideration the effects of water percolation and the effects of flood events the following is the expected sequence of failures in the tunnel, if no protective steps are implemented, illustrated by the two dimensional views in **Figs. 34-38**.

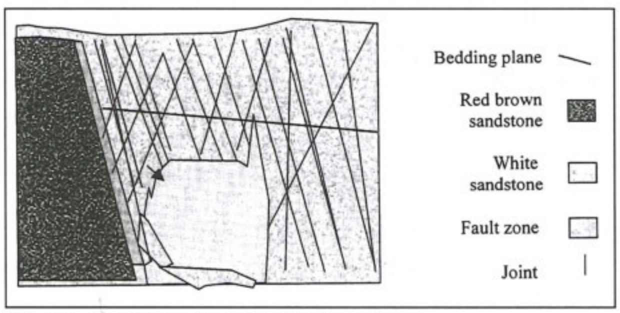
I. The original situation, with the factors encountered before any new failures start (**Fig. 34**).
II. The effect of floods wash out the lower portion of the side walls, at the same time percolating water affects the stability of the rock mass, particularly the block marked in black on (**Fig. 35**).
III. The blocks resting above the joint planes slide



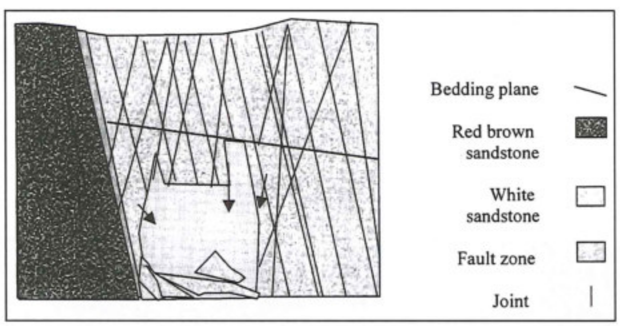
34. The Mudhlim tunnel before failure starts.



35. Effect of flood on the side wall of the tunnel.



36. Blocks sliding along the fracture planes.

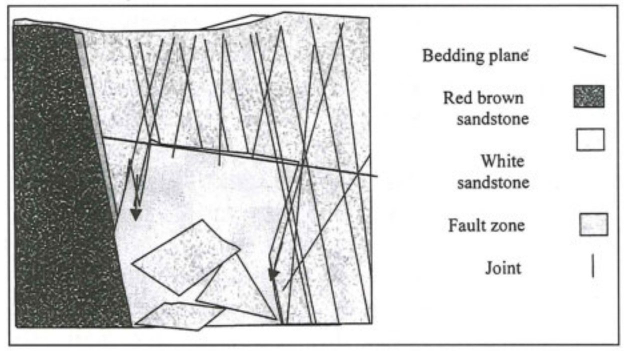


37. Blocks falling and sliding along joint planes.

along those planes in the east wall, and along the fault plane in the west wall. This will allow the blocks in the ceiling to fall (**Fig. 36**).

IV. Other blocks will then be free to fall from the ceiling and slide along the existing planes from the side walls (**Fig. 37**). This process will continue simultaneously and/or progressively until the flat bedding plane forms the ceiling (**Fig. 38**).

The above represents a two dimensional analy-



38. Features continue until a bedding plane forms the ceiling.

sis of the current situation. Exact conditions are more complicated (i.e. 5 major sets of joints intersecting together on the ceiling and side walls, dipping in different, unfavourable directions). Whereas only two joint sets and the bedding plane are enough to create block failure, more serious collapse is anticipated due to the high number of joint sets.

Most of these joint sets are vertical or dip in unfavourable directions and the intersection of three of them can create a single block. The risk of this block falling depends on the other conditions discussed earlier.

At the entrance of the tunnel one of the joints is oblique to the wall direction. The joint opening has been enlarged by surface water runoff, a process that acts progressively in a downstream direction. In addition there is the degradation effect on the side walls which act as the support for this block. This block will become unstable and will fall down at the stage where the supporting and shear strength are reduced to a level that cannot hold the block's own weight.

There is a simple equation for the stability factor: stability=resistance/weight. The main factors which influence resistance are support and shear strength.

A protective measure is essential for preventing reduction of resistance in order to stop these blocks falling and inside the tunnel the loss of support of the ceiling will become critical if blocks in the side walls gradually slide down. Between 20-45m from the entrance of the tunnel, the conditions are very poor; some very large blocks have already slipped along the joint planes from the right wall after floods washed out its toe support. The rock is highly weathered, the cement between its grains having been gradually washed out by water action. Towards the outlet of the tunnel, the left wall along the fault plane is still intact, whereas parts of this wall upstream have been washed out.

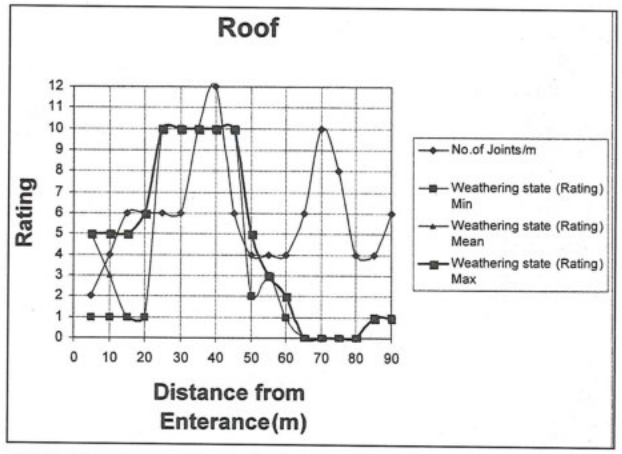
All the factors discussed have been inspected inside the tunnel, evaluated, rated and presented as a set of failure risk maps (combined in one map in **(Fig. 39)**. The blocks with the greatest risk of falling or sliding were rated 15 (blocks in immediate danger) and the safe blocks were rated 0. This scale (0-15) is the range used by software that evaluates the number of joints per area, rock mass strength and state of weathering.

Each of these conditions was evaluated separately and the risk rates were calculated using the value shown in **Fig. 40**, and were automatically processed at reasonable scale, and contoured to produce the risk maps.

The risk maps show that the left wall is less affected and is in better condition than the ceiling and the right wall. This is due to the nature and quality of the rock mass, which is composed of very strong, well-cemented sandstone. The joints are filled with well-cemented sandstone that is more resistant to weathering than the intact rock.

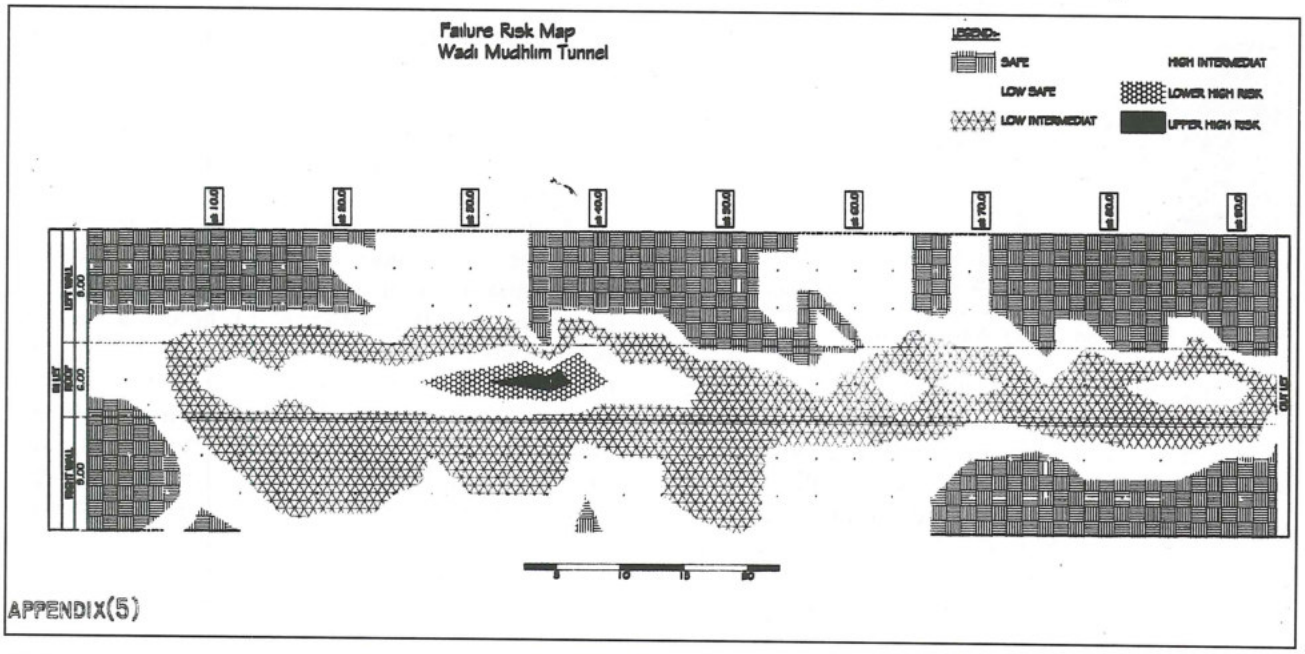
At a distance of 30-40m from the inlet, both walls of the tunnel are rated as low-intermediate risk, which puts the ceiling in this part at its greatest risk, because, without the support of the blocks in the wall, the situation becomes critical. Some of the walls have been washed out by flash floods and the situation between the ceiling and the left wall is indeed critical.

The conditions in the ceiling are more complicated and the risk is much higher than for the walls because of joint sets. The state of weathering of the joints is the main controlling factor, along with the number of intersecting joint sets. The ceiling is composed of poorly cemented white sandstone and water percolation and infiltration play a major role in enlarging the joint planes and releasing the blocks from the intact surrounding rock, allowing them to fall.



40. Risk rating of block fall in tunnel ceiling.

The right hand wall is classified as intermediate to high risk and is composed of poorly-cemented, highly jointed sandstone. The effect of flood erosion on the wall is very high, especially in the lower portion, in addition to the effect of percolating water along the joint. The erosion of the lower portion of the wall will remove parts of the toe support of higher blocks; this in turn will allow the second block to slide along the joint plane which dips towards the tunnel wall. This process is progressive towards the east after each flood and will widen the tunnel to a stage where the ceiling becomes un-



39. Combined risk map showing the ceiling in the centre and the two side walls.

stable. This will result in the ceiling's collapse (probably at a spot approximately 35m from the entrance where the situation is classified as upper high risk or immediate danger).

Conclusions

- Wādī al-Mudhlim in general is stratigraphically positioned within the Cambrian sandstone (Umm Ishrin formation) and the lower portion of the Ordovician sandstone (Disi formation). Structurally Petra is located within a highly complicated fault zone.
- The wadi itself is major normal fault trending N-S, where the red brown sandstone (Umm Ishrin formation) of the western wall rests against the white sandstone (Disi formation) to the east.
- Five joint sets were measured along the tunnel walls, some are parallel to the fault and the others crossing diagonally.
- The tunnel walls are parallel to the fault plane and major joint sets.
- The tunnel area is extensively affected by weathering, especially the ceiling and the right wall, the white sandstone having lower resistance to weathering than the red brown sandstone.
- Many failures were observed in the tunnel due to the free fall of blocks from the ceiling and blocks sliding from the side walls.
- Three major factors control the stability of the tunnel: structures (i.e. the fault, joints), the weathering status of rock mass and floods.
- In some areas the instability of the tunnel reaches critical level.

General Recommendations

In order to stabilize the conditions in the area of study, improve safety and minimize the damaging effects of flash floods to the tunnel, monuments and the immediate surrounding environment, the following interventions are measures that need to be implemented urgently.

Clearance of the collapse within the Sīq al-Mudhlim tunnel

The recent collapse within the tunnel was cleared in 2003, thus improving the flow through it and reducing the erosive power of flash floods.

The Construction of Three Check Dams

Immediate construction of three check dams is needed to stop movement of sediment in sector MS1 between the two culverts of Wādī Mūsā and the Mövenpick Hotel and from continuing down into the Sīq al-Mudhlim. Sediment accumulation could flatten the wadi bed slope, which would lead to better flow conditions in the future.

The Construction of a Detention Basin

The study revealed the need to construct a detention basin at the bottom of sector MS3. The basin is needed to absorb the flood peak and increase the detention time before flowing through the Sīq al-Mudhlim.

Clearance of the Roof of the Tunnel

All soil on the roof of the tunnel should to be cleared as soon as possible, to increase the runoff from the top of the tunnel. This includes removing the vegetation to prevent further root weathering. All cracks and openings need to be cleaned and filled with an impermeable material to prevent water percolating directly along the cracks and all depressions should to be treated to prevent water accumulation. The ceiling of the tunnel needs to be supported with a steel structure should the above recommendations be delayed, to avoid the high possibility of its collapse under the current conditions.

The Construction of Two Main Dams

Two dams need to be constructed, in sectors MS5 and MS11. The expected reservoir capacities are 3200 and 2500 respectively. Based on the site conditions, it is recommended to construct the dams as cascade structures as these would fit site requirements, work conditions and stability criteria.

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Petra National Trust,
PO Box 815480, Amman 11180
pnt@nets.com.jo
www.petranationaltrust.com

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