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Hydrology of the combination irrigation system in the Wadi Faynan, Jordan

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Abstract

The field system of the Wadi Faynan in southern Jordan were fed by an ancient combination irrigation system that incorporated runoff farming and diversion irrigation techniques. The hydraulic characteristics of this system were most probably designed to take advantage of the confluence of three tributary streams. A theoretical model of discharge produced by runoff is based on contemporary ground conditions and historic climate reconstructions. The design principles of the main hydraulic features are examined and velocity and discharge measurements in principal conveyance irrigation channels are reconstructed. The design of this hydraulic system took into account the environmental constraints and opportunities of the area and maximized different sources of water in the catchment using various techniques of water collection.

Keywords: Jordan; semi-arid; runoff farming; diversion systems, hydrological reconstruction

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1. Introduction

Irrigation has been a significant component of dryland (Beaumont, 1993) agriculture from Neolithic times. Scarce water supplies were either collected or diverted by local inhabitants using wells, adit systems, cisterns, water harvesting, floodwater farming, run-off farming and diversion systems to name but a few techniques (Biswas, 1967; Helms 1981; Hunt et al., 1986; Bruins et al., 1986; Gilbertson, 1986; Barker, 1996; Gilbertson et al., 2004; Prinz & Malik, 2002; Elvin, 2004; Barker et al., 2007). However knowledge of the hydrological and hydraulic characteristics of these systems remains scant in spite of the abundance of archaeological studies of such systems (Stager, 1976; Barker, 1996; Burri and Petitta, 2005; Barker et al., 2007). This seems or the more puzzling given the fact that the techniques for doing such hydrological surveys have been known about since the late 1960s and 1970s (Evenari et al., 1968; Farrington & Park, 1978) and have only occasionally re-emerged despite acceptance that simple and quick to use techniques can provide valuable information that can be applied to present day conditions (Gale & Hunt, 1986) whilst GIS and DEM technology allows for improvements of these techniques where a more long term survey can be used (Lavee et al., 1997; Ackermann et al., 2008; Frot et al., 2008). Furthermore, understanding of the interactive use of different irrigation techniques in conjunction with each other is poor. Thus the complexity of these irrigated dryland agricultural systems is often underplayed. This paper in part seeks to begin the processes of redressing this balance by conducting a hydrological investigation of one such ancient and abandoned irrigation system in the Wadi Faynan in southern Jordan. This is now a semi-arid region where the availability of water and good farmland is scarce and the area sparsely populated by Bedouin and National Park wardens from the Dana Nature Reserve. The Wadi Faynan is the principal river of the area it today experiences large seasonal fluctuations in discharge. A series of tributary rivers dissect the steep scarp on the western edge of the upland plateau of the Edom Mountains and flow westwards for 30 km into the Wadi Arabah. The tributaries from north to south are known as the Dana, Ghuwayr and Shayqar (Fig. 1).

2. The Wadi Faynan Study site

Remnants of the ancient Nabatean, Roman and Byzantine settlement known as Khirbet Faynan sits at the confluence of these three tributary rivers, however, human activity in this area occurred much earlier with evidence from the Neolithic (al-Najjar et al., 1990; Simmons and al-Najjar, 1996) and Palaeolithic (Barker et al., 2007). Indeed archaeological work in the Wadi Faynan has revealed evidence of a complex field system associated with these settlements dating back to around 4000 BC (Barker et al., 1996; Barker, 2002; Hunt et al., 2007; Barker et al., 2007; Bar-Yusef, 2008).

Nonetheless what remains today of the Faynan field system are those fields developed to support a relatively large population involved in the extractive and polluting metal producing industries of the area (Pyatt et al.,1999; Barker, 2002; Grattan et al., 2004; 2007; Barker et al., 2007). Tied in with some, but by no means all of these fields, are some sophisticated hydraulic structures, such as a reservoir, aqueduct, conduits, dams and sluice systems. These seem to be a planned irrigated agricultural system designed to support a local centre for copper extraction (see Barker et al., 1997; 1998; 2007).

3. Climate and weather

In order to calculate how efficiently these irrigation structures operated and in what hydraulic capacity it was first necessary to review current climatic and weather conditions and compare these to current understanding of the climate in the Roman/Byzantine period. Western Jordan today is recognized as having a semi-arid climate (Doppler et al., 2002) whereas during the Roman/Byzantine period it is suggested that climate was somewhat wetter than today (Hunt et al., 2007:1306). Perhaps more important to reconstructing operational levels of flow in conduits and runoff generation are local weather patterns. Unfortunately local weather patterns are not discernable in palaeo-records, therefore recent local weather records were consulted and historical patterns of weather assumed from these data to build into the runoff farming reconstruction. The mean annual rainfall taken at Shaubak climate station, the nearest official monitoring site to the Wadi Faynan, between 1938 and 1987 was 315 mm (Department of Meteorology, 1999). These rains mainly fell between November and April with 50 % of this precipitation falling between the months of December and January. In a wet year there may be as many as 5-7 major rain storms, whereas in dry years the figure maybe lower, with only 3-4 rain storms capable of generating significant runoff (Tarik Abu-Hawa, *pers. comm.*). The intensity of these storms can be high with 150 mm/24 hours recorded at Dana Secondary School station in 1998. The length of these storms, however, tends to be short in the region of 30 minutes to two hours. Dewfall becomes important in summer and autumn, whilst humidity is highest (70 %) between December and February. With a mean annual temperature of 14-16° C and mean daily potential evaporation at 3.68

mm, with a range of 1.35 mm in December to 6.05 mm in July (Department of Meteorology, 1999), there is a xeric moisture regime (i.e. soil is completely dry in entirety 45 or more consecutive days within the 4 months that follow the summer solstice in 6 or more years out of 10) and thermic temperature regime (i.e. mean annual soil temperature 15° C - 22° C and the difference between mean summer and winter soil temperature is more than 5° C at a depth of 50 cm). Thus there is a soil moisture deficit for much of the year, with the precipitation:evaporation ratio closest to unity in January and February (see Al-Weshah, 1992). These data suggest that during all periods irrigation has been necessary to support agriculture.

4. Reconstructing runoff farming in field system WF4

In the layout of ancient walls there is evidence for runoff farming in the WF3, 4, 5 and 6 field systems, but because of the limited time hydraulic measures could only be taken from one location, field system WF4 (see Fig. 2). A headwall (approximately 0.65 km) runs above the WF4 and WF5 field systems. This contains gaps (interpreted as probable spillways and sluice systems) and diverts water onto these field systems. Other runoff was diverted from small wadis into wide channels with silty beds (surface roughness 0.03 mm) and stone lined banks (surface roughness 6 mm), although undercutting now makes it difficult to see where this would have occurred exactly. These systems probably received their major phase of usage during the Roman period according to their structure and surface pottery (Barker et al., 1999; 2007).

The catchment area for runoff generation was potentially large with the fan sediments of the Ghuwayr and Shayqar linked to the Faynan fluvial terrace deposits (see McLaren et al., 2004), however, their generally lower slope angles (0.017°`-0.174°) and distance from source suggest that their importance for runoff farming systems would be less important than nearby hamada slopes because of poor hydrological connectivity (see Gale & Hunt, 1986; van Wesemael et al., 1998; Ackermann et al., 2008; Frot et al., 2008). Rather it is more likely that only the small hill observable in Fig. 3 was active in runoff generation. Since Roman times these slopes have probably had a strong ground armor and were denuded, a view supported by charcoal samples collected from the mining sites which indicate that Roman miners had to import their fuelwood from the Jordanian plateau (Engel 1993; Barker, 2002; Barker et al., 2007; Hunt et al., 2007). It may be possible that farmers cleared these slopes to some degree to increase the rapidity and amount of runoff, an ancient practice observed in the nearby Negev region (Ackermann et al., 2008).

In terms of soil structure the studied slopes have fine strong silty soils with surface stone armor (average diameter approx. 0.01-0.02 m). Slopes are generally steep on the hill close to the wall systems (0.5-0.643°), but ease off directly in front of the wall systems (0.017-0.174°). It is suggested that the slopes directly upslope of the headwall act as a conduit for runoff during short intense storms, although this process has not been observed. It appears from observation that runoff is concentrated in shallow channels on the slopes close to the headwall system have preferential routeways which surface runoff flows down. These appear to coincide with the location of spillways/sluices along the walls.

Infiltration rates from both the contributing area and field systems were calculated using a simple inner and outer ring infiltrometer. Water was applied in a controlled way to an inner ring area surrounded by a previously flooded outer ring area. The final infiltration figure was calculated from.

$$\frac{\text{Drop in tube (cm) x area of tube (cm}^2\text{) x 10 x 60}}{\text{area of ring (cm}^2\text{) x no of minutes}}$$

Infiltration rates were in the order of 80 - 90 mmh^{-1} in the contributing catchment area, which means that only high intensity rainfall events would contribute to surface run-off (Table 1). These infiltration capacities must be treated with caution as they do not take account of the impact of surface slaking resulting from large rainfall droplet sizes and high intensity rainfall. There rates also give no indication of the importance of sub-surface flows to Wadi discharges.

As mentioned earlier, besides runoff generation from adjacent slopes, water was also conveyed to the irrigated fields in an open channel between sites WF4 and WF5 and field systems WF3 and WF6 (see Fig. 2). This channel is ~1 m wide and ~0.4 m deep and runs for approximately 500 m. It is clear from field layouts and topography that water control was not a feature of all fields and that soil conservation was more of a priority in many fields. The techniques for soil and water conservation are similar and therefore it is sometimes difficult to establish the importance and priority for individual field systems. Infiltration rates throughout both ploughed and unploughed field systems were in the order of 29-46 mmh^{-1} (Table 1) which is lower than in the catchment system. The high density of pottery, lithics and slag on the surface of many fields would mean that the surface roughness was in the order of 0.01-0.05 m. It is possible that these superficial deposits were used as a form of deliberate manuring as observed in contemporary irrigated fields in the Wadi Dana (Barker et al., 1998). Alternatively, the same surface materials could have been used to reduce runoff from fields by slowing the velocity of the water and promoting infiltration, a strategy observed in floodwater farming systems in the Negev Desert

(Evenari et al., 1964; 1968; 1982). This strategy also has the benefit of reducing soil erosion in these fields.

5. Estimating runoff generation

An estimate of runoff generation from adjacent slopes to the floodwater farmed fields during a 1 hour design storm of 100 $mmhr^{-1}$ has been calculated using an empirically based simple model using a similar approach to Gale & Hunt (1986). This model incorporated simplified parameters down a theoretical slope which conformed to a number of assumptions described below.

Firstly, the model run was designed to apply the Darcy-Weisbach and Colebrook-White equations using measurements from both the contributing area and field systems to allow the calculation of overland flow (discharge) for each 1 m^2 unit in the flood water farming system. The discharge output from each m^2 downslope was cumulatively input into the next m^2 downslope, assuming a simplified linear downslope direction of flow and so on for a design catchment that reflects both travel time in the contributing area including the upper and lower slopes (53.5m) and through the distribution network (30 m) of the field systems and a cross sectional length of the field boundaries of ~650m .

The depth of overland flow was calculated from:

$$(((\text{rainfall } (mmh^{-1}) - \text{infiltration capacity } (mmh^{-1})/60(\text{mins}))/60(\text{secs})/1000)$$

An assumption of completely dry antecedent soil moisture conditions is made, and the model takes no account of possible soil slaking and compaction during heavy rainfall and ignores any possible contribution from Hortonian overland flow. Rounded up infiltration figures taken from the contributing catchment area and field systems (Table 1) were fed into the model at appropriate stages in the downslope profile to replicate the overland flow process. The Darcy-Weisbach equation was used to calculate velocity and cumulative discharge for each 1 m^2 section of the contributing slope (Fig. 4) whilst the overall runoff contributing area was calculated at 84 m slope length (see Fig. 5) x 1500 m width. Thus, for the main runoff generating slopes the cumulative discharge generated for a 1 hour design storm of 100 $mmhr^{-1}$ was 0.122 m^3s^{-1}. The inter-field open distribution channel between sites WF4 and 5 and field systems 3 and 6 could have operated at a maximum velocity of 3.69 ms^{-1} resulting in bankfull discharge of 1.48 m^3s^{-1}. The amount of additional water per field was calculated by dividing the discharge figures (converted to litres) for both the run off fields and the inter-field channel with the average field size calculated from the area encompassed by WF3, WF4, WF5 and WF6 (1664 m^2). This produces an additional volume of water of 0.07 l/m^2 in the runoff fields and 0.89 l/m^2 in the fields fed by the inter-field channel. These values must be added to the 100 l/m^2 rainfall expected on each field under a 100 $mmhr^{-1}$ rainstorm. Thus, it is clear that the relative proportion of additional water is small in comparison to that provided by the rainfall. It does, however, appear that the volumes talked about here are similar to those found nowadays in the humid areas of the Mediterranean coast of Israel (Hillel, 1992). That said this form of irrigated agriculture would only have remained viable during a period of predictable and regular intensive rain events.

6. Diversion System

Frank (1934) and McQuitty (1995) described an aqueduct which conveyed water from the Wadi Ghuwayr to a reservoir and single-towered penstock type water mill that was probably constructed and in operation during the Roman/Byzantine period (Wikander 2000:371-400). Evidence for this conduit was found high up in the Wadi Ghuwayr that forms part of a diversion/slope offtake system mapped in Grattan et al., (2007:93) that has a length of ~1.8 kms.

Headworks for this system would appear to have been located close to the current gauging station where flows are perennial, however, a large stone cut channel, now partially filled with a large rock, is the first definite evidence for the start of the conduit system (Fig. 6). Just a few metres on there is further evidence for this channel and an additional conduit carved into the rock face, the lower of which appears to be older (Fig. 7). Approximately 0.25 km downstream, there are two locations where stone faced walls support a single plastered channel (Fig. 7). This channel, which follows a contour along the side of the Wadi Ghuwayr, appears to be remnants of the younger higher channel. Remnants of the older and lower channel are more fragmentary, which relates to differing preservation.

On the side of a rocky abutment lower down the Wadi Ghuwayr there is further evidence for three channels existing, the higher channel is 1.5 m above the middle channel, which in turn is 1.5 m above the lower channel (Fig. 7). Scour lines along the rock confirm this observation. The highest channel (width 0.7 m, depth 1 m) appears to be the oldest and contains evidence of Roman/Byzantine plaster. The middle channel is the largest (width at base 0.7 m, width at top 0.8 m, depth 1.5 m) and also contains fragments of Roman/Byzantine plaster. The youngest, lowest and smallest channel (width at base 0.5 m, width at top 1 m, depth 0.5 m) has no plaster. It is possible that this channel may have been lined with mud. The lower of these conduits also has a branch in it which suggests that this supplied water to fields in this area. There is a fall of 16 m on the youngest channel between this point and the headworks: the oldest channel falls 11 m in the same distance.

The first clear evidence again for the channel is a line of stones and fragments of plaster on the right hand bank of the Wadi Shayqar (see Figure 1). This evidence suggests that the conduit flowed from north to south immediately before taking a right angle turn into the Roman/Byzantine aqueduct a view supported by previous work (see Barker et al. 2007:60). The aqueduct was an impressive structure which spanned the Wadi Shayqar (Fig. 8). It incorporated a series of at least 12 arches (Barker et al. 2007) the last of which collapsed on the 5 April 1998. The one remaining archway prior to this date had a span of 3 m and a height of 3 m. The section of conduit still surviving is 31.8 m in length. The aqueduct has two clear phases of development with a lower channel replaced by a higher channel. Both channels were rectangular and lined with Roman/Byzantine smooth plaster (average thickness 0.01-0.03 m, friction = 0.3 mm). The higher channel (width 0.52, depth 0.2 m, slope 0.0197°) lies on top of the cobble filled lower channel which has slightly larger dimensions (width 0.55 m, depth 0.25 m, 0.017° slope). In both cases it is probable that the true depth of these channels was in the order of around 0.4 m.

From the aqueduct there is little evidence for the course of the conduit not until a 6.6 m section of channel (0.5 m width, 0.3 m depth, 0.0126 slope) is clearly seen again at the intake to the Roman/Byzantine reservoir. From here water was passed through a sediment trap (1.74 m width, 1.2 m depth, 1.8 length) before entering the principal reservoir that measures 31 m x 22.4 m [with 0.36 m of fill] and a total depth of 4.03 m to the overflow, providing a cubic capacity of 2798 m^3 (see Fig. 3). Lying on top of the west reservoir wall, next to a series of steps, there is another section of channel (0.4 m width, 0.3 m depth, 9.3 m length, 0.0039 slope) which flows towards the line of a partially buried reservoir overflow 1 m below this channel. The purpose of this channel was to provide a greater head of water than derived from the overflow to drive the Roman water mill. This, plus the design of the reservoir suggests that the water held in the reservoir was not used to drive the water mill or provide water for conduit irrigation. It must have been used primarily as a drinking water source or for small scale hand irrigation. An EDM survey shot from the Khirbet Faynan indicates a drop in altitude of 8.1 m over ~ 300 m between the aqueduct and reservoir (see Grattan et al., 2007).

Using Kay's (1983) equation below:

$$\frac{\text{Difference in altitude (m) from headworks to end point}}{\text{Length of channel (m)}} \times 100 = \text{slope \%}$$

The average slope percentage of 2.7% is quite large for this short stretch of the conveyance channel. It seems likely that the steep slope may be caused by geological uplift in the area (McLaren et al., 2004) and thus not be representative of the true slope angle of the channel when in operation.

The over-the-top Roman water mill has a leat of 15.8 m (slope 0.0029) and dimensions (width 0.45 m depth 0.4 m) similar to the intake of the reservoir. The water ran along the stone covered leat before dropping through a vertical circular shaft with a diameter of 0.2 m and a length of c. 1.5 m. This narrow shaft opened up into a wider roundish chamber, which now contains rubble, approximately 1.5 m wide and 2.4 m deep (Fig. 9). Thus, the structure resembles a bottle cistern rather than the

Arubah Pentock Mill described by McQuitty (1995). This structure requires re-excavation, but it is assumed that the lower chamber is where the water wheel was housed as there does not appear to be evidence of further outbuildings. The function of the reservoir seems to be hydrologically separate from that of the water mill, which contradicts previous suggestions by Frank (1934). It is worth noting that there is no evidence for a channel beyond the mill. This would appear at first sight to be a wasteful and inappropriate end use for water in a semi-arid area, unless the water had been contaminated by ores possibly crushed in the mill. The field systems directly below the mill (WF2) appear, however, to have been laid out in such a way as to spread and capture water running off from the tail race of the mill (see Fig. 2). The U shape of these fields and cross sectional wall structure implies the use of liman style irrigation strategies which rely on the impoundment and infiltration of water into soils (see Potchter et al., 2008). This, however, remains a hypothesis, though localised farming did take place 50 years ago inside this ancient field system (Carol Palmer, *pers. comm*. 1997).

Discharge Figures

Reconstructing discharge in these channels requires the use of the Darcy-Weisbach equation (Gale & Hunt, 1986). Using channel full dimensions from the remaining structures and a range of friction factors (e) (Moody 1944; Ackers and White, 1973) which account for good (e = 0.3), normal (e = 0.6) and poor (e = 1.5) quality trowelled lime plaster surfaces a series of mean flow velocities and bank full discharges have been produced (Table 2). The use of a smooth plaster along the bed and sides of the conduit significantly reduced friction levels and shear stress within the channel.

The results demonstrate that at high friction levels water supply is extremely low and at times inoperative. Thus, channel lining must have been maintained at a reasonable to good level for the system to have been operative. Studies of contemporary diversion irrigation systems show that these systems are rarely operated at full capacity (Crook, 1997). Reasons for this include the scarcity of water, danger from rupture, changing seasonal requirements for water by agriculturists and scheduling and allocation requirements. Whilst there is a perennial water supply in the Wadi Ghuwayr originating from springs in the limestone uplands, this discharge varies seasonally such that the conduit could only operate at wetter times of the year according to contemporary climatic conditions. Annual variation in the timing of rainfall in the hills will also have impacted on the timing of conduit use. The contemporary gauging station in the Wadi Ghuwayr which is located at roughly the point at which water would have been diverted into the conduit provides data for contemporary discharge levels. It is important to note that because of the perennial input to the reservoir it is not possible to use the volume of the reservoir as an indicator of population size.

Khirbet Faynan Barrage

This is a substantial Roman/Byzantine barrage that is most probably a water impoundment feature the origin of the barrage is carbon dated at around 1800-1900 years ago and as such it is part of the Khirbet Faynan complex (Grattan et al., 2007).

The hydrological role of this barrage is not clear, however, this structure is well constructed and partially buried. It is found immediately north of Khirbet Faynan, and was investigated at sites 5017 and 5512 by Hunt et al., 2007 (Fig. 10). Sediments found behind the barrage are highly polluted by ancient mine slag deposits and it is very likely that water quality was affected by these (Pyatt et al., 1999; Grattan et al. 2007:94) to such an extent that the water was too toxic to drink and could not be used for irrigated agriculture.

Water Quality

Waters in the upper parts of Wadis Ghuwayr and Dana are perennial (see Fig. 6). A contemporary measure of water quality (Table 3) shows that the pH and alkalinity of these waters is very high as a result of their source in the high limestone plateau. This means that that water in the conduit system, if used for irrigation, would require careful management to prevent problems of structural damage to the soil and reduced infiltration capacities in the fields.

If this water had been used incorrectly on field systems one could expect to find evaporative and precipitate features in field soils, but these are not present. Likewise in the recently drip irrigated fields in the Wadi Faynan (i.e. last 40 years) there is no visual evidence for such problems occurring. This suggests that conduit water was either carefully managed, not used for irrigation (unlikely considering field layouts) or was only diverted during storm events when the Wadi discharge would be extremely diluted by rainfall and rapid surface runoff.

Water stored in the reservoir would be prone to evaporation and as a result of this salts would increase in concentration. The lack of evidence for a roof to this structure suggests that water storage would be for short periods only, although a cycle of filling and emptying may have occurred, particularly during the night. This suggests that Nabatean and Roman/Byzantine farmers had a good understanding of water quality and its implications for irrigated farming.

The conduit channel passes a number of slag heaps. Unless the conduit was covered or sealed one would expect leachate problems during rainfall events. The high levels of heavy metals detected in these slags (Pyatt et al., 1998; 2000: Grattan et al., 2007) suggest that there would be episodic major pollution events in the conduit system and possibly also in some runoff fed fields. Certainly sediments in the conduit would be expected to bio-accumulate such problems as this is a major feature of sediments behind the Khirbet Faynan barrage (Pyatt et al., 1998; 2000: Grattan et al., 2005; 2007). There is some χrf evidence for raised levels of heavy metals occurring in channels and field sediments so toxicity could have been a problem.

Discussion

The discussion first looks at the runoff system in field systems WF3, WF4, WF5 and WF6 then turns to the Roman/Byzantine diversion system before discussing the implications of these findings upon the whole combined irrigation system. The use of floodwater and runoff farming techniques by prehistoric farmers is frequently cited as an ingenious adaptation to agriculturally marginal, semi-arid environments (Evenari et al., 1982; Gilbertson, 1986; Gilbertson and Hunt, 1990; van Wesemael et al., 1998). By diverting and retaining water and soil in small hill-slope plots it was possible to overcome rainfall limitations by capturing runoff from a larger watershed in a concentrated area. However the vulnerability of runoff farming in the Wadi

Faynan was acute, owing to limited water resources that only gained efficiency when a sufficiently large storm to generate overland flow occurred. This view is supported by small overall discharge figures derived from runoff farming in comparison to other studies (Gale and Hunt, 2006; Ackermann et al., 2007) that suggest it would take a storm somewhere in the magnitude of the design storm used in the model for the runoff system to irrigate the Faynan field systems. Besides this, the level of infiltration recorded in the WF4 systems points to the contributing area for runoff generation being no greater than 84 m in distance from the fields thus supporting the view that only the small hill directly in front of the system (~120 m) contributed towards runoff generation. Similar studies in Almeria, Spain support this idea of a small contributing area (Frot et al., 2008). The infrequency of 100 $mmhr^{-1}$ storm events makes the runoff system vulnerable to climate vagaries unless there was either a storage capacity built in to the system or supplemental sources of water. Gale and Hunt (1986) also suggest that modifications to surface coverage are very important in the generation of surface runoff in such marginal systems. Evidence from the Faynan runoff catchment system supports this view. Thus, in order for these fields to receive sufficient water for crop growth, the internal open distribution channel would need to operate in conjunction with the runoff farming. This defines irrigation in the Wadi Faynan as a combination irrigation system.

Another, less frequently discussed, consequence of runoff farming is its potential for exacerbating erosion and rendering agricultural plots less fertile. Indeed, many prehistoric check dams and other features were probably attempts to counteract the loss of soil in these already marginal agricultural efforts (Farrington and Park 1978; Gilbertson et al., 1984 Prinz and Malik 2002). Runoff techniques were effective in producing crops in otherwise non-arable locations, yet it was necessary to maintain a precarious balance between the benefits of runoff farming and the potential for soil degradation. This vulnerability is in part expressed through what looks like the deliberate spreading of what were probably the contents of middens that contained mining slag and lithics to help maintain soil fertility on the WF4 field systems. These may also have served albeit unintentionally to increase runoff generation and reduce erosion. Perhaps more alarmingly, geochemical studies (Grattan et al., 2005; 2007) indicate extraordinarily high levels of metallurgical pollution in Roman times, many times higher than modern safety limits, not just for copper but for lead, barium, and many other toxins. This combined with a problem of gully erosion that lowered the depth of water flow below that of the diversion walls meant that the runoff farming systems increasingly became less effective in WF4. Thus, this field evidence supports the view that farming in the area collapsed relatively quickly, in the late Roman period (Barker et al., 1997; 1998; 1999).

Moving on to the diversion offtake system from the Wadi Ghuwayr, it is clear from the technical expertise demonstrated that water control structures and water management was highly developed in the Wadi Faynan area from a very early period. The successive sequence of transfer between water control structures and end uses associated with the Roman/Byzantine conduit system seemed logical in order to take advantage of these perennial waters. The evidence for three phases/levels of conduits near the headworks and two phases of channel development (which appear roughly from the same era according to construction techniques) at the aqueduct site, however, suggests that there has been a need to make adjustments to the level of the conduit at different sites and at different times. It seems logical to assume that these adjustments would have been made to improve the hydrological efficiency of the channel. A number of hypothesis result from these findings:-

- There may have been more than one conveyance channel operating i.e. one to irrigate farmland upstream of the aqueduct and another to supply the reservoir.
- Neo-tectonic activity has produced uplift in the area of the reservoir and mill relative to the headworks.
- Deflation and down cutting in Wadi systems may be significant in this area (McClaren et al., 2004).
- Sedimentation upstream of the headworks necessitated raising the headworks and offtake channel.
- A desire to maximise output from the system led to the desire to increase the head of water in the channel thereby increasing discharge.
- A mixture of one or more of these factors.

There was the potential to irrigate land upstream of the Shayqar. The majority of water, however, supplied the Roman/Byzantine reservoir and then the mill. The relationship between the runoff farming and diversion system remains uncertain as does the inter-field relationship between soil and water conservation. It is clear that early epochs relied solely on runoff farming techniques, however, these are only clearly evident in units WF4 and 5. Besides this, there is circumstantial evidence for runoff farming being utilized in other fields with the existence of possible baffles and sluices and the use of small water harvesting cisterns in Bronze Age fields (Barker *pers. comm.*1998; Hunt et al., 2007). The amount of water available to run-off farmers for farming was periodically more than that available to people through the open conduit diversion system and reservoir. A comparison of the average discharge figures obtained from the Roman/Byzantine channel with those found in the inter-field channel of the runoff system shows that discharge could be up to 97.6% greater in the later. However, runoff would only have been induced during sporadic and unreliable intensive storm events that created floodwaters, thus making this a hybrid runoff/floodwater farming system, where as the supply of water to the conduit was much more reliable and dependent on a much larger catchment area. This may explain why there is no widespread use of cisterns as found in other areas of Jordan (see AbdelKhaleq and Alhaj Ahmed, 2007) which suggest water was less scarce here than in other areas. However run-off farming could only be run as a complementary strategy to other forms of irrigation in the Wadi Faynan. This makes this a classic example of a combination irrigation system (see Vincent, 1995). Thus, the location of the field systems at the confluence of three Wadis was clearly a wise strategy to maximize water resources in what was and still is a marginal area to farm. It seems likely that abandonment of these systems relates as much to changing socio-economic conditions as it does to physical changes to the climate and landscape although the latter have had major implications for the maintenance of the diversion system and possibly also runoff fields particularly as drying occurred at the end of the Roman period in the region (Heim et al., 1997). The decline of the copper mining industry appears as important. Similar socio-economic reasons are given for the decline of ancient irrigation systems in other parts of the ancient World (Hack, 1942; Farrington & Park, 1978).

Conclusion

The hydrological palimpsest is difficult to unravel nonetheless a number of key points arise from the reconstruction work done to date:

- The use of combination irrigation and drinking water collection systems allowed for irrigated farming that was an essential support to dry farming in other parts of the Wadi Faynan field systems. Mining activities were only possible in the Wadi Faynan by creating an agricultural surplus to support the large resident workforce.

- Three separate conveyance channels along the diversion irrigation system may reflect a period or readjustment or even expansion in the hydrological system before its eventual decline and abandonment. The interpretation of these changes is made difficult because of geomorphological change and potential neo-tectonic activity in the area.

- There is little evidence for a decline in water quality being a potential source of abandonment based on contemporary hydrological conditions.

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Table 1: Infiltration rates in the Wadi Faynan (N30 37 18.5 E035 29 13.6)

Site Number	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**
Site Description	Upper Hamada Above WF3 & WF4	Lower Hamada Above WF3 & WF4	Below Mill [Colluvial]	Parallel channel WF3 [Colluvial]	Unit WF13 Bronze Age Field (unploughed)	Unit WF13 Bronze Age Field (ploughed in last 2 years)	Lower field WF16 Probably not irrigated
Slope Angle	3^{o}	8^{o}	2^{o}	2.5^{o}	1.5^{o}	2^{o}	3^{o}
Infiltration Rate	89.7 mmh^{-1}	79.2 mmh^{-1}	43.8 mmh^{-1}	45.2 mmh^{-1}	36.1 mmh^{-1}	29 mmh^{-1}	33.3 mmh^{-1}

Table 2: Mean flow velocity and bankfull discharges in the Roman/Byzantine conduit system

Site	*e*	Velocity ms^{-1}	X-sectional area m^2	Discharge m^3s^{-1}
Upper aqueduct	0.3	0.592	0.104	0.062
	0.6	0.337	0.104	0.035
	1.5	Inoperative		
Lower aqueduct	0.3	0.652	0.138	0.09
	0.6	0.396	0.138	0.055
	1.5	0.058	0.138	0.008
Reservoir intake	0.3	0.51	0.113	0.058
	0.6	0.301	0.113	0.034
	1.5	0.023	0.113	0.003
Reservoir conduit	0.3	0.29	0.12	0.035
	0.6	0.173	0.12	0.021
	1.5	0.019	0.12	0.002
Mill leat	0.3	0.305	0.18	0.055
	0.6	0.195	0.18	0.035
	1.5	0.049	0.18	0.009

Table 3: Water quality data

Wadi Ghuweir Sites	Water Temperature ^{o}C @ around midday	pH	Conductivity dSm^{-1}
Initially after 1st sink heading upstream	16.9	8.18	1.13
Immediately after side Wadi confluence	18.8	8.85	0.76
Headworks of Roman/Byzantine conduit system	24	9.11	0.75
Wadi Dana	25.6	8.7	1.3

List of Figures

A preliminary investigation into an ancient and abandoned combination irrigation system in the Wadi Faynan

Darren Crook[a]

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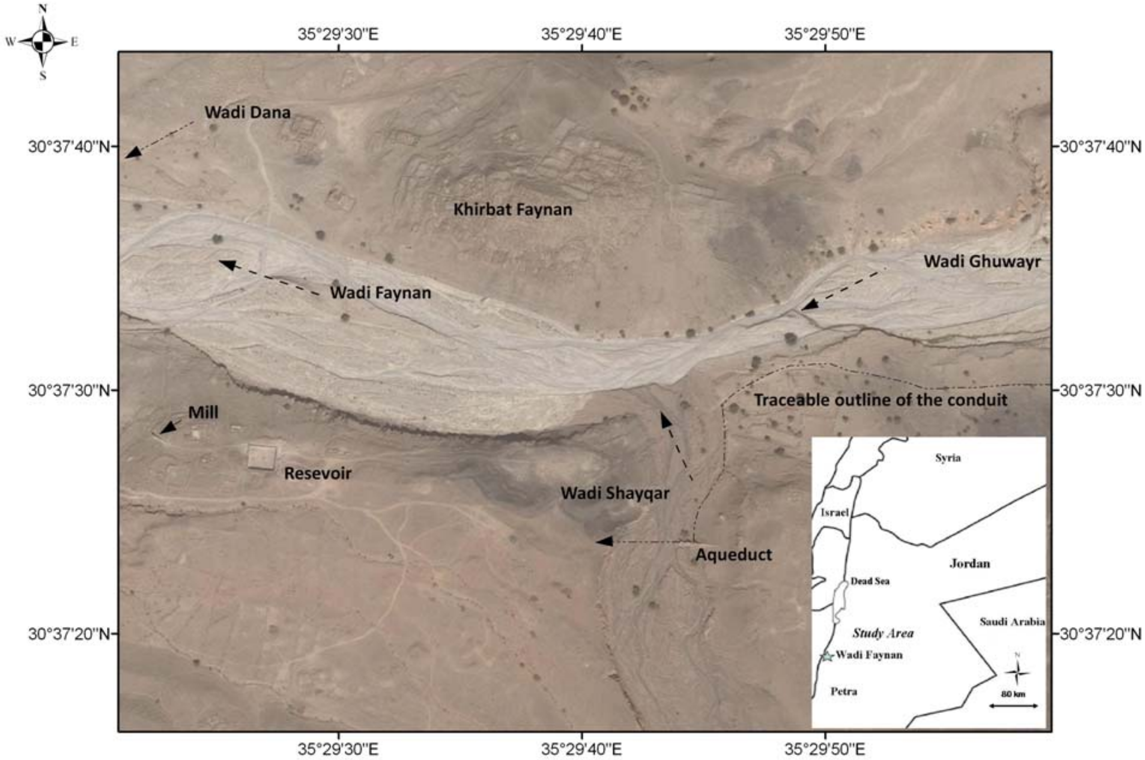
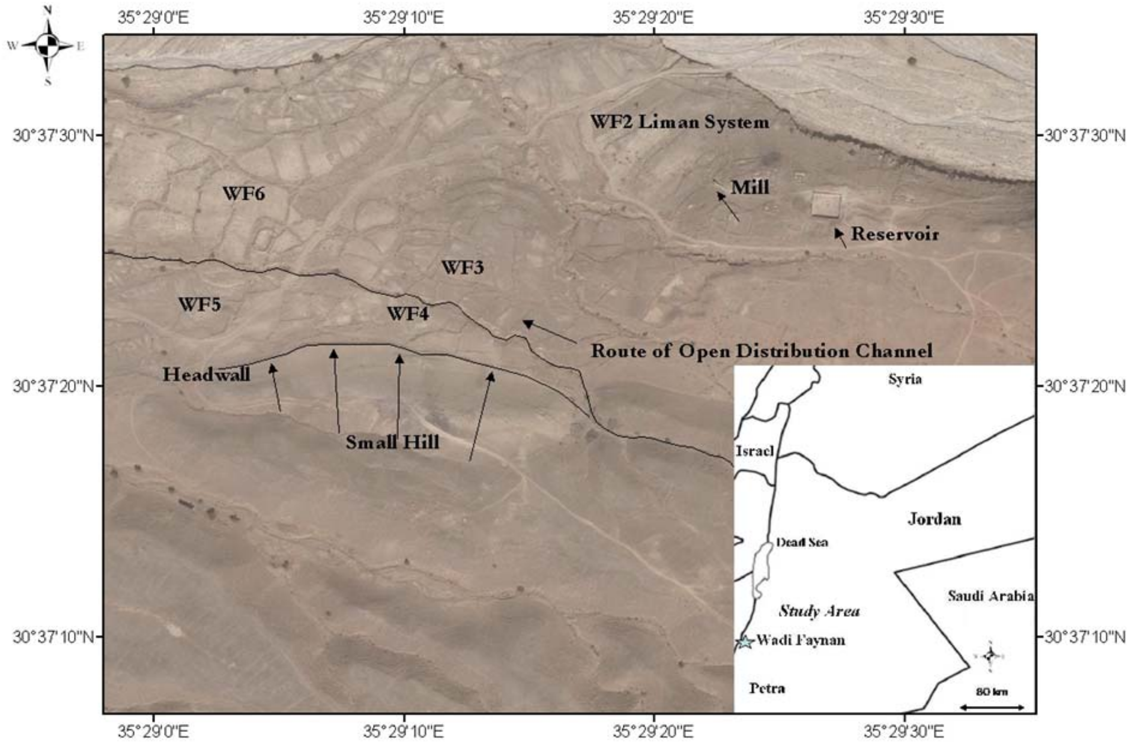


N
W
E
S
35°29'30"E
35°29'40"E
35°29'50"E
30°37'40"N
30°37'30"N
30°37'20"N
Wadi Dana
Khirbat Faynan
Wadi Faynan
Wadi Ghuwayr
Traceable outline of the conduit
Mill
Resevoir
Wadi Shayqar
Aqueduct
Syria
Israel
Jordan
Dead Sea
Study Area
Wadi Faynan
Saudi Arabia
Petra


35°29'0"E
35°29'10"E
35°29'20"E
35°29'30"E
30°37'30"N
30°37'20"N
30°37'10"N
WF2 Liman System
Mill
Reservoir
WF6
WF3
WF5
WF4
Route of Open Distribution Channel
Headwall
Small Hill
Syria
Israel
Jordan
Dead Sea
Saudi Arabia
Study Area
Wadi Faynan
Petra
80 km

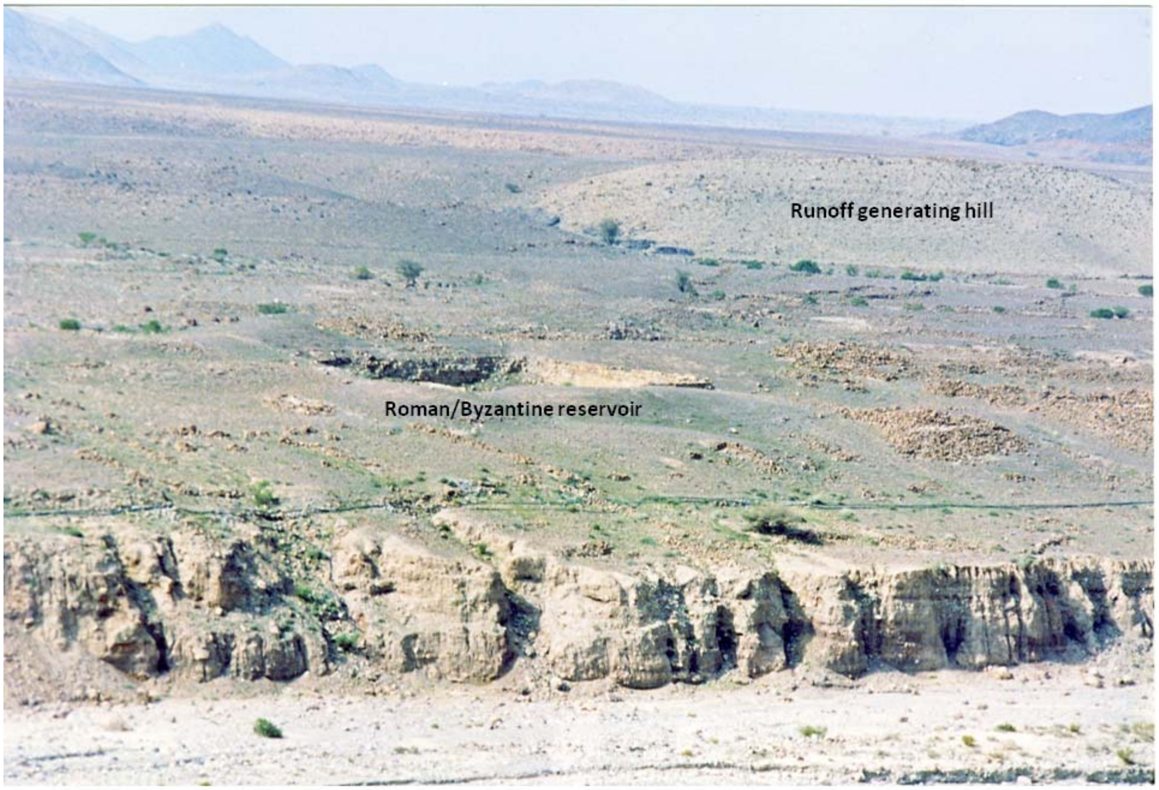

Runoff generating hill
Roman/Byzantine reservoir

Fig. 4: Darcy-Weisbach equation

mean flow velocity $(u) = (8.g.\mathrm{R.\ S}/f)^{0.5}$

where:
g = acceleration due to gravity
R = hydraulic radius
S = slope
and the value of f is found from the Colebrook-White equation:

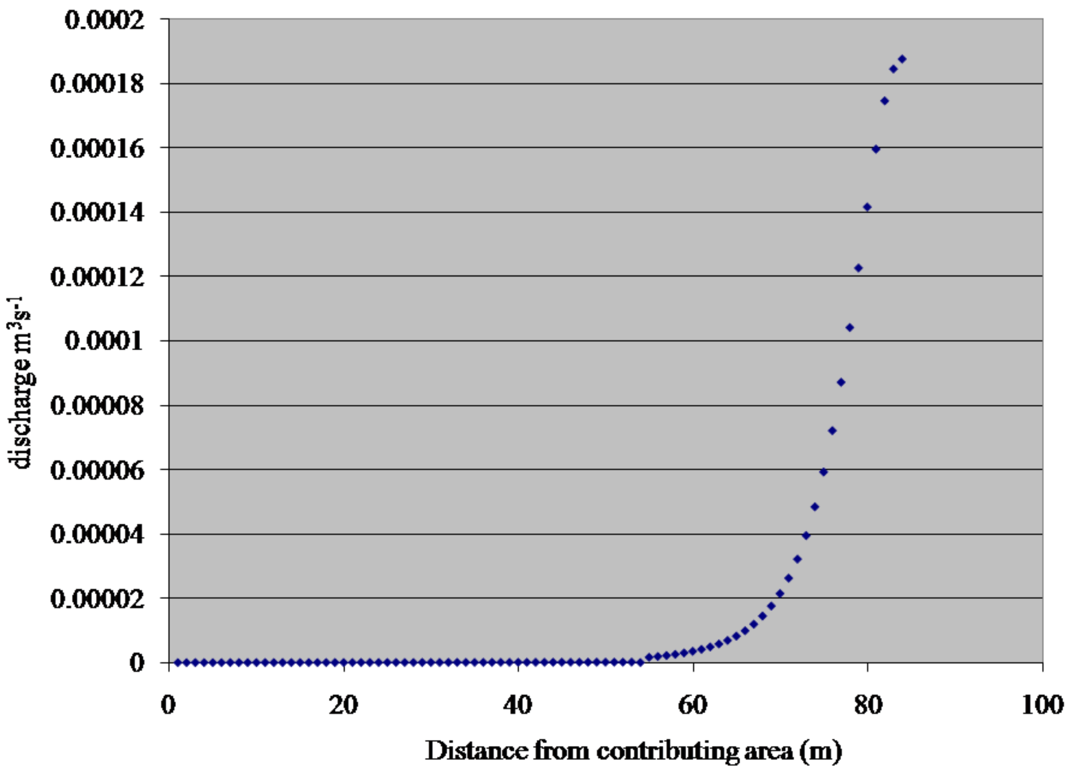
$$1/f^{0.5} = 2.03 \log_{10} (k.\mathrm{R}'/e)$$

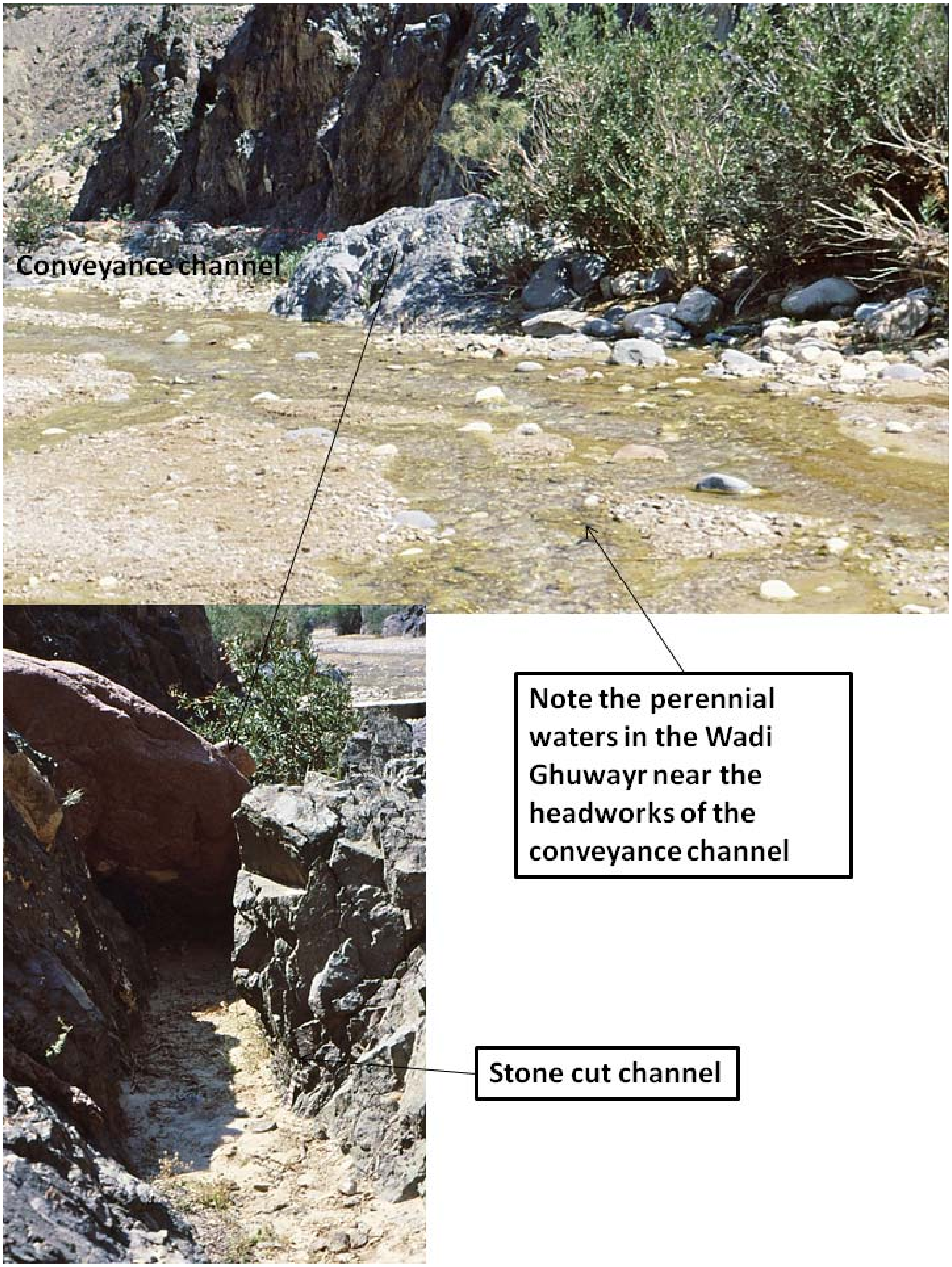
where:
k = a coefficient dependent on channel cross-sectional shape
R' = effective hydraulic radius
e = bed roughness

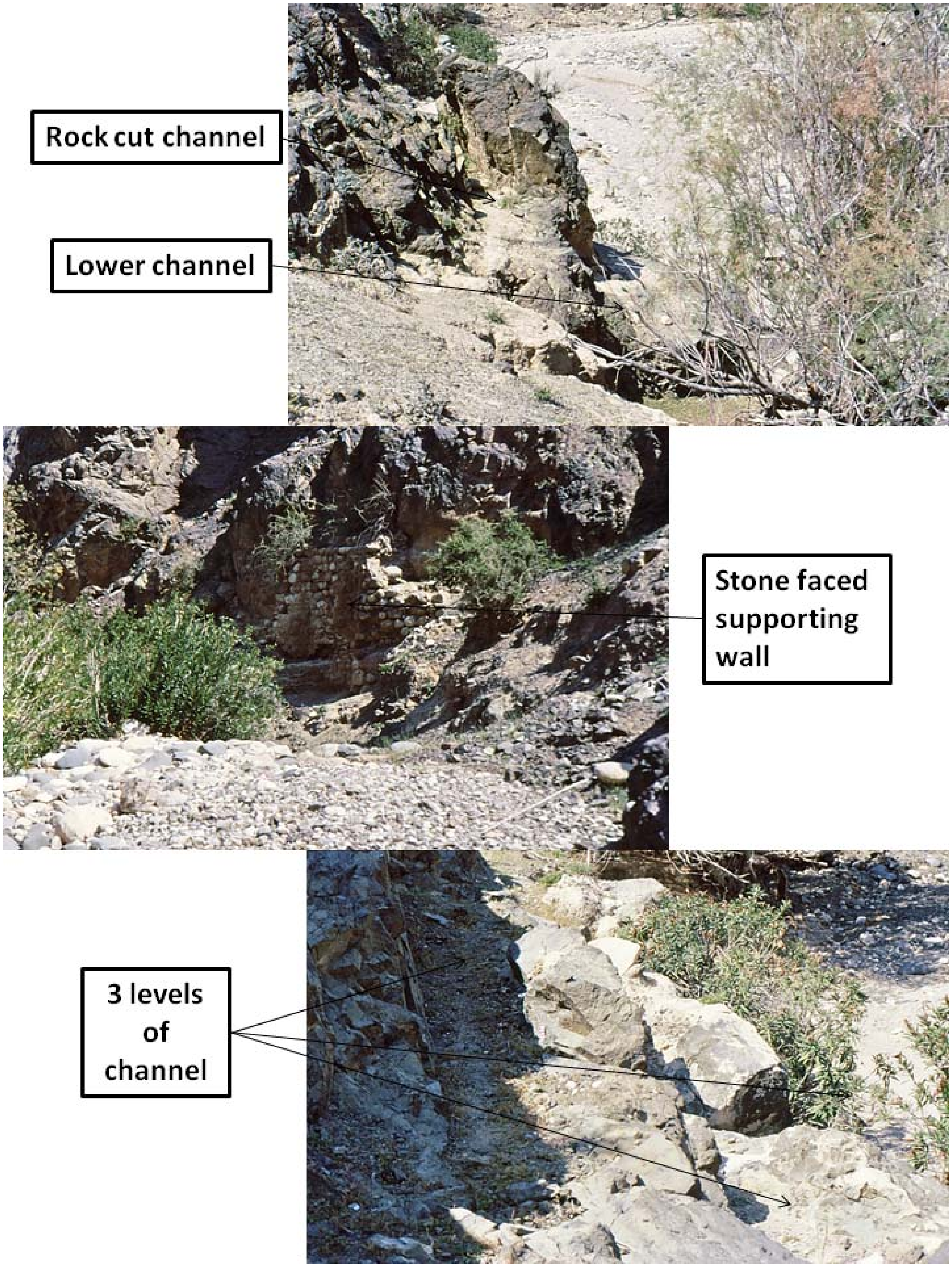
The value of k, 11.1, is based on the assumption of an infinitely wide channel (Hey, 1979). Mannings e for bare or sparsely vegetated ground = 0.03
Thus, discharge (Q) is calculated from the continuity equation:

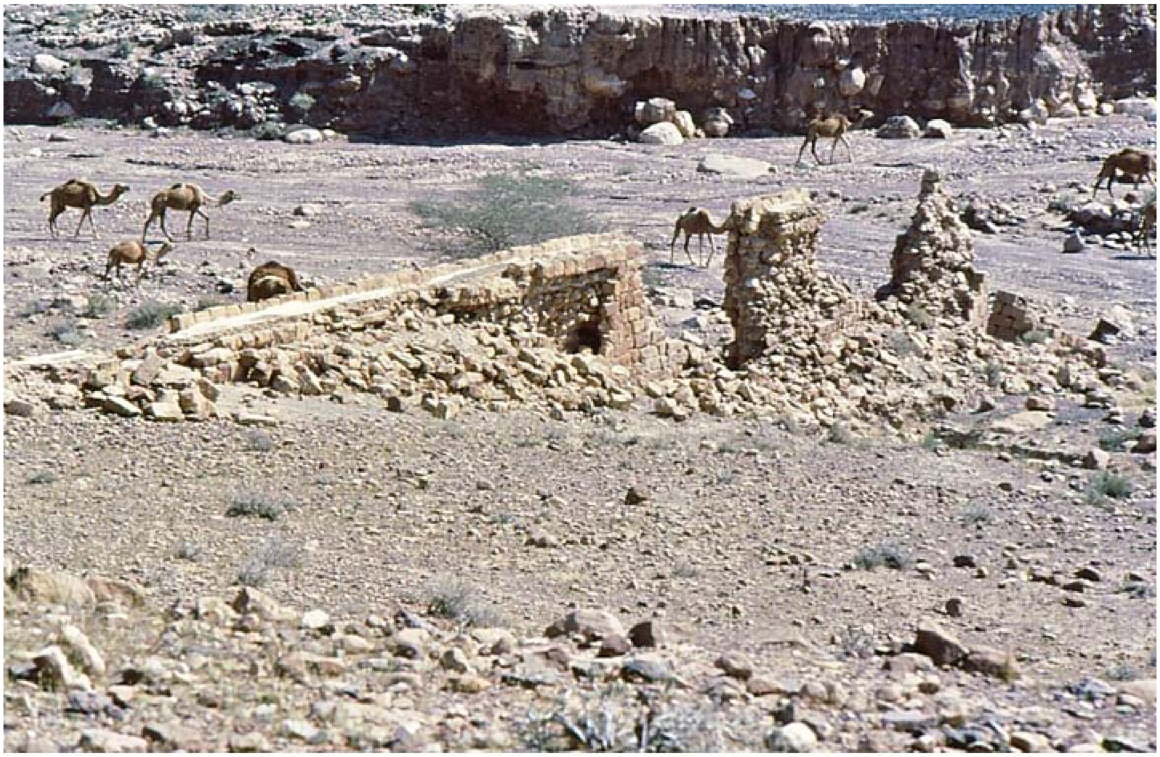
$$Q = \bar{u}.a$$

where a = cross sectional area


0.0002
0.00018
0.00016
0.00014
0.00012
0.0001
0.00008
0.00006
0.00004
0.00002
0
discharge m3s-1
0
20
40
60
80
100
Distance from contributing area (m)


Conveyance channel
Note the perennial waters in the Wadi Ghuwayr near the headworks of the conveyance channel
Stone cut channel


Rock cut channel
Lower channel
Stone faced supporting wall
3 levels of channel



Note the two levels of lime plastered channel


Reservoir
Mill leat
Vertical circular
shaft of the mill


Barrage
Sediment Infill