

## 1.2 Irrigation and landscape: An interdisciplinary approach

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### **ABSTRACT**

Studying irrigation history is studying the history of civilisation in dry areas where the natural environment and water infrastructure are closely connected. Yet, surprisingly little is known about the ways irrigation provided the material base for civilisations to prosper. Our knowledge how irrigation developed as interplay between hydraulic and humans is limited, presumably because that kind of knowledge is highly interdisciplinary in nature. Several aspects of water use in irrigation systems need to be explored, including timing and distribution, in order to study how water fluxes on different time scales could be incorporated in archaeological research. This paper discusses irrigation in the Zerqa triangle in the Jordan Valley where water tapped from the Zerqa River was transported to the fields through open canals under gravity. The settlement patterns found in the valley suggest close connections to the canal system from the Iron Age onwards. Physical aspects of the irrigated landscape will be explored by basic hydrological and hydraulic modelling.

### **KEYWORDS**

**irrigation, Jordan, explorative modelling, water management**

## INTRODUCTION

A most fascinating aspect of irrigation is the close connection between civilisation and the natural environment in which water infrastructure acts as interplay. Many civilisations of the past have used irrigation to feed their population. Intensified production provided a relatively secure food source for a larger population as it enabled the peasant population to produce a surplus to support the non-peasant population. Food security enabled development of city kingdoms in many regions: Mesopotamia, Egypt, the Indus-valley, China, Mexico and (coastal) Peru (Scarborough 2003). Because of the importance of irrigation, it has been well studied. The well-known Hydraulic Hypothesis is based on manipulation of water from larger streams for irrigating areas without reliable rainfall. Despite this valuable research, what has been stated by one author more than 25 years ago is still a valid comment. 'Much of the archaeological literature on irrigation canals merely notes their presence at a certain period(s) and records their association with sites. It may describe or even classify the main features of an irrigation system [...] but does not fully elucidate the technology, hydraulics or hydrology of the canals. Even where excavations into canals have been carried out, the researchers have not used their data to its full potential [...].' (Farrington 1980).

In other words, how the irrigation systems underlying the ancient civilisations may have functioned, is not clear at all. Irrigation systems, spatial conglomerates of artefacts, are supposed to supply crops with water. This requires both physical distribution facilities to transport water and socio-political arrangements to coordinate between actors in dealing with water flows. User strategies have an impact on the system and the system constrains user actions. Hydraulic behaviour of irrigation systems resulting from human action is partly constraining and partly enabling human action. Irrigation systems have structuring properties (see Sewell 2005; Ertsen 2010; Ertsen & Van Nooijen 2009). Analysing irrigation development through hydraulic and hydrological modelling will build understanding on how these systems may have been operated at the various stages of their development, how water was distributed and how agriculture was organised, in relation to the settlement patterns of the regions.

As much as elsewhere, human survival in the Zerqa triangle in the Jordan Valley depended on the human ability to adapt to the natural environment, not just in the reactive sense, but also in the proactive sense of shaping the environment, with a major instrument being irrigation. Temperatures are very high because of the low altitude of 300 metres below mean sea level. Average winter temperature is 15 degrees Centigrade, while the summer average is 32 and maximum daily temperatures of 40 to 45 degrees are quite common. Rain falls only between November and April, with an average of about 290 millimetres a year, although annual variability is quite large. Theoretically the average falls just within the limit that is considered the minimum for dry-farming, but frequent droughts would make it impossible to sustain a stable society of some size without a more secured water supply from irrigation. The Zerqa triangle has been extensively studied within the Settling the Steppe-project, and I use the extensive data available through these studies in this paper (Kaptijn 2009; see also Kaptijn et al. 2005; Van der Kooij 2007). My interest is to develop ideas on how irrigation in the Zerqa triangle may have functioned. In this paper I focus on the relation between crop water needs, rainfall and irrigation strategies. I start with a little background on irrigation in the Zerqa triangle, followed by a discussion on crop water requirements and water availability. Then I develop some first ideas about irrigation system management and discuss some first modelling results. The paper ends with an outlook to future work.

## IRRIGATION IN THE ZERQA TRIANGLE

Modern irrigation in the Jordan Valley is generally drip irrigation, but before the 1960s, a canal system existed that may well have a long history. Available 19th- and early 20th-century itineraries suggest that the few people who lived in the Valley at this time used canals that tapped water from the river Zerqa (Kaptijn 2009). Aerial photographs taken in the 1940s clearly show a number of small canals that brought water to fields located at considerable distance from the river. On unpublished blueprints from the East Ghor canal, a construction project after World War II, the old canal irrigation system is depicted in great detail (fig. 1; Kaptijn 2009). Three main channels tapped water from the Zerqa, with a series of secondary and tertiary canals irrigating a considerable area. Maintenance and construction of these canals will have been labour intensive and required a communal effort as a large area was dependent on a single primary channel. The Jordan Valley was only sparsely populated and the aerial photographs show that only a small part of the entire system was in use. It is unlikely that 19th-century farmers developed a large irrigation system which they used only partially. In 1920, inhabitants of the Zerqa Triangle stated that 'neither they nor their fathers made these channels; they only cleaned existing ones' (Kaptijn 2009).

As several sources suggest that the Jordan Valley was devoid of sedentary population during the 17th and 18th century, the only likely large-scale farming society from which 20th-century people could

Figure 1. Schematic overview of the irrigation system of the 19th and 20th century (Kaptijn 2009).

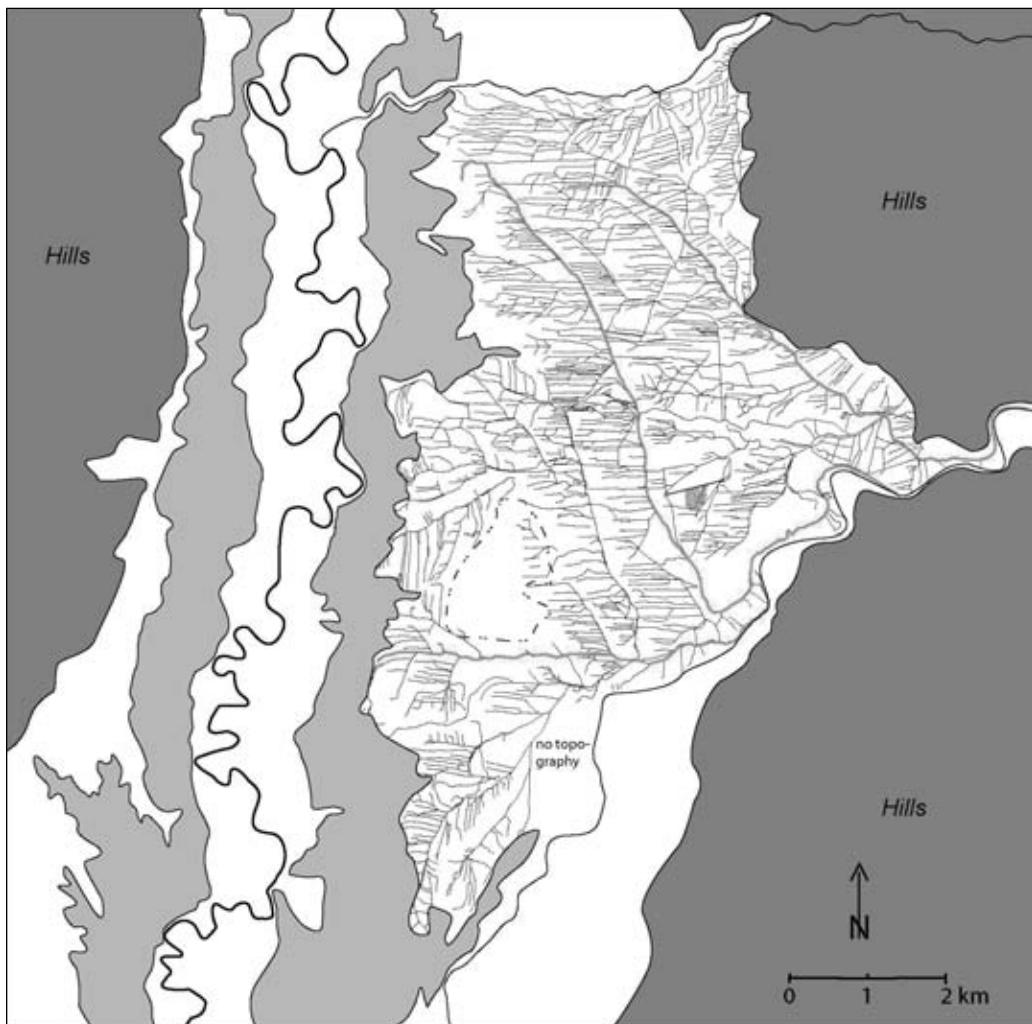




Figure 2. Irrigation canals and associated sugar mills in the Mamluk period (Kaptijn 2009).

have inherited the irrigation system was that the Mamluk period (1260-1500 AD), when the Valley was widely used for sugar cane cultivation. Sugar cane is a tropical crop that grows in summer and needs large amounts of water. In the Jordan Valley climate, irrigation would have been vital. Sugar was produced by crushing the cane and boiling the juice down until raw sugar remained. This was done locally in watermills. Several of these watermills or sugar-related sites have been excavated. All known mills are located along the three main irrigation channels known in the 20th century or along known wadis (fig. 2). It is thus likely that the 20th-century irrigation system dates back at least to the Mamluk period.

Although there is no direct evidence in the form of excavated canals it is likely that a similar system of canal irrigation existed in the Iron Age II period (1000-540 BC). From the number of tells it is clear that the Zerqa Triangle was rather densely populated during this period (Kaptijn 2009). Although the large number of tells which were found are usually small, it is unlikely that many small contemporary communities could have existed in this dry area over a prolonged time. Furthermore, archaeobotanical data show crops were grown that cannot have been cultivated without irrigation in this area, for example large quantities of flax. There is no direct evidence on how irrigation was practised but the presence of tells in

the middle of the plain in combination with the layout of the Zerqa triangle suggests that canals would have provided the water. The potential routes of canals are limited by several features in the landscape, and the main channels may have been located at more or less the same place as during pre-modern times.

A different system of cultivation was probably practised in the Late Chalcolithic and Early Bronze Age (3600-2300 BC). It is clear that during the Early Bronze I period many small sites were located in the plain and along permanent water courses like the river Zerqa and the Wadi al-Ghor. In the Early Bronze II and III periods this system changed and habitation shifted from the valley plain to the foothills. Instead of several small villages people grouped together in larger walled settlements. It is clear that during the Early Bronze Age the Zerqa Triangle was quite densely occupied. The climate was probably slightly more humid than today, but not so much that higher evaporation rates, and thus crop growth, could be sustained by rainfall only. As the rivers and wadis were at that time not as deeply incised as today, they would have submerged the area regularly. The hypothesis that Early Bronze Age communities practised farming in the floodplains could very well apply to the Zerqa Triangle (Kaptijn 2009).

## **CROPS AND WATER**

Let us turn first to the orders of magnitude of water needed for crop production. How much of this water need was met by rain and how much by river flow? What are the differences per crop and what can be said about the temporal pattern of water required? As far as can be established, the agricultural techniques open to the different communities in the different periods discussed above would have been comparable. This means that the agricultural base for which crop water requirement can be determined are comparable. Cropping patterns for the different periods were determined using archaeobotanical data from excavations, ethnographical analogies and the few ancient texts available (Kaptijn 2009). For the Iron Age, the data show high amounts of cereals, both in seeds as in number of samples. Cereals need significantly more water when they are almost mature than when they are germinating. The Mamluk period is in some respects considerably different to any other period. Within other periods all evidence points to simple subsistence farming for the local market, whereas the Mamluk period saw large-scale sugar cane farming in the valley. Sugar cane may have taken as much land as possible, even if this came at the expense of the local population's subsistence (Kaptijn 2009). The villagers probably worked as employees on the plantations, with food crops being grown on fields that lay fallow from sugar cane.

For all cropping patterns, crop water calculations were made using the simple standard approach as given by the Food and Agricultural Organisation (FAO). In this approach, crop development is divided in four different stages, from emerging to maturing. The duration of each developmental stage differs per crop and the total amount of time needed to reach maturity. In the Jordan Valley the high temperatures cause plants to mature more rapidly than average. Agricultural reports from the early 20th century have documented the growing seasons of the most common crops. These timing aspects have been used to make the FAO data applicable to the specifics of the Jordan Valley. In each phase, a so-called crop coefficient expresses how the crop transpiration relates to potential evapotranspiration. For example, when emerging, crops have shorter roots and cannot evaporate as much as when mature. The climatic data on potential evapotranspiration and rainfall were available at the agricultural station in the Zerqa triangle. River flow data were taken from Nedeco (1969). Although the climate in the region definitely changed

over time and discharge and rainfall will have differed, these differences are supposed to be not extremely large. Climatic proxy data suggest that the Iron Age II period may have been comparable to today, but that the Mamluk period might have been more humid (Kaptijn 2009). There is much more to be discussed about changes in climatic conditions in the region and the impact on human activities (see for example, Issar & Zohar 2004), but for the present study, modern data on rainfall, temperature and river discharge were used for analysis.

Taking the modern climate data and combining them with the crop data, it can be determined how much water a crop needs (Kaptijn 2009). These water demands can be connected to a real stretch of land actually cultivated when the total cropping pattern is known. For the cropping system documented in the 1950s in this part of the valley, frequencies and amounts of cultivated crops were determined. First, it must be noted that as much as 30% of the land lay fallow. A large proportion was taken up by cereals, while fruit and vegetable took up only small plots of land. Using the relative importance of crops, the water demands can be translated into irrigable hectares given the water availability in the river. On average, the base flow of the Zerqa River is usually sufficient to irrigate the area potentially served by irrigation canals tapping from the river Zerqa, which is about 45 km<sup>2</sup>. However, this simple estimation assumes that people were able to use all of the water in the river, which is unlikely. Furthermore, when taking the driest year of the data series, much lower areas of about 18 km<sup>2</sup> appear to be available for irrigation. The Mamluk period is again different, as a dry year would typically sustain only twelve irrigated km<sup>2</sup>. Sugar cane is a highly water-demanding crop.

## WATER REQUIREMENT AND IRRIGATION STRATEGIES

Existing studies on physical properties of ancient irrigation tend to apply straightforward calculation routines, similar like the one presented above. A simple example shows the potential of adding a little more real-world complexity. For an ancient system in Peru, water requirements for cotton were calculated with a similar approach (in the FAO Cropwat model; Ertsen & Van der Spek 2009) which proved to be comparable to what Nordt et al. (2004) found. The resulting water use scenario, which was supposed to be optimal, as it sustained maximum crop transpiration throughout the growing period, was used as input

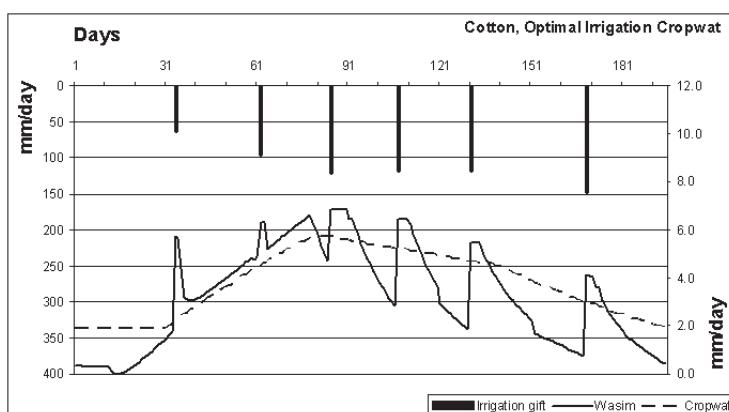
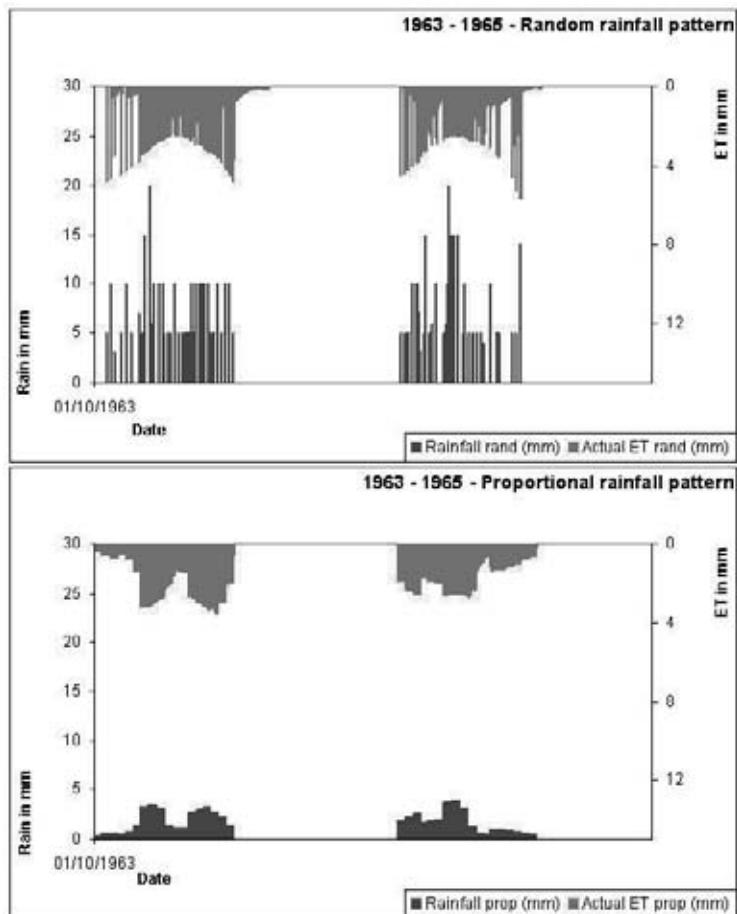


Figure 3. Comparing two different models (Ertsen & Van der Spek 2009).

for WaSim, a one-dimensional soil-water balance model, which includes soil water movements, even on a very basic level (Hess et al. 2000). Figure 3 shows that the physically more realistic results suggest that the crop cannot sustain evapotranspiration for full growth, as water moves down from the root zone to deeper soil layers. The downside is that WaSim applies a daily time step and thus needs daily values for forcing inputs like rainfall, evaporation or other data. Obviously, daily data for 3,000 years ago are hardly available. In case of the Peruvian case modelled above, this can be overcome, as there is no rainfall in summer and evaporation does not change that quickly.

In the Jordan case, however, rainfall is an important aspect of the water balance. Rainfall data are available on a monthly basis. The question then is how to translate these monthly values to daily values. Usually some kind of rainfall generating algorithm would be applied for that (as in Whitehead et al. 2008). For this paper I applied two simple, different methods, as I only want to make the point that it matters how rainfall data are included in the analysis. Figure 4 shows these two methods for a two-year time frame of the total sample. The lower graph shows rainfall and resulting evapotranspiration (in WaSim) for rain-fed wheat when rainfall is proportionally distributed over a month; the upper graph shows what happens in case rainfall is randomly distributed over a month. It is worth noting that the total amount of water available for crops is the same, although the shape of the graphs may suggest otherwise. The

Figure 4. Two different daily rainfall patterns.



sketchy rainfall pattern of the upper graph is reflected in sketchy evapotranspiration, as crop and soil only evaporate what is actually available. However, sketchy evapotranspiration may mean that the crop develops less smoothly than average rainfall may suggest. Especially young crops, with their underdeveloped root system, are vulnerable for water stress. When water stress occurs early in the growing season, the crop may actually not develop and as such not profit from better water availability later in the season.

An extreme case of such a situation is presented in figure 5. The figure shows crop evapotranspiration, and thus growth, of a wheat crop planted in November with rainfall averaged over the period. Calculations were made in Aquacrop, a crop water model developed by FAO. One of the crops was modelled starting in dry soil at wilting point (wp), when crops cannot extract the water in the soil anymore. The other crop was modelled with the soil being at field capacity (fc), meaning that the soil contains the maximum amount of water for crops to be extracted. As the continuous and growing evapotranspiration suggests, this crop managed to develop. The model indicated that the crop produced a biomass of 8.3 ton per hectare in Aquacrop, with an actual yield of wheat of 2.5 tons per hectare. The dry crop did produce biomass, but only 0.135 tons per hectare, which never managed to produce any yield. The exact numbers are not that important, but the difference between considerable biomass and no biomass is. The figure not only shows the importance of starting conditions when studying irrigation and yields, but also suggests that irrigation may not have been needed, as rain fed agriculture is an option on the Zerqa plain when soils can be brought to field capacity.

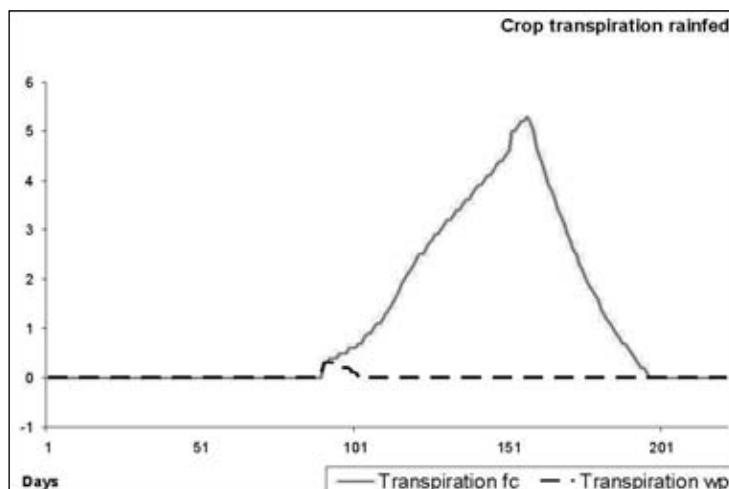


Figure 5. Dry and wet starting conditions.

In many canal irrigation situations comparable with the Zerqa triangle, the start of the growing season is largely determined by rainfall. Typically, irrigation is not the single source of water in these situations, but is used to supplement the rainfall which will be available most of the years in the growing season. The crop is sown when the rain has started, with irrigation starting once the river flow has increased because of the rains. This means that in the early season crops would need to survive on rainfall. For farmers, determining the optimal starting moments can be difficult. If one is too early, because of some good rains which are not sustained, the young crop may not prosper because of drought conditions in the early

stage. In case of late sowing, the water availability is probably fine, but the crop may grow too long in the dry season after the wet months. As shown above, the difference between a good choice and a bad one may actually be defined as having a harvest or not. Calculations confirmed that a single 'rescue' irrigation gift relatively late in the season, 100 days after sowing and with dry starting conditions, is too late, as the crop already died. Full irrigation during the entire season will not have been needed, at least not to sustain crops like wheat, which can grow on deeper soil moisture as soon as its roots can reach deeper layers. For crops like vegetables, which have roots that go less deep and need more frequent watering, irrigation may have been more vital during the growing cycle, with less water required per gift. Issues like starting date, rainfall patterns, crops and irrigation needs are highly dependent on each other, and thus need to be carefully studied before conclusions on feasibility of crop strategies can be drawn. Further and more detailed analysis would need to include statistically developed scenarios of rainfall and other variables. Based on the analysis so far, I will take one step further in another direction and develop some ideas about irrigation in the Zerqa triangle, especially about system management.

## **IRRIGATION MANAGEMENT**

Climatic conditions as in the Zerqa triangle typically would give irrigation a supplemental character. Typically, in supplemental irrigation the issue is not to match the crop water requirements exactly, but to give the crop a boost every now and then during the season to avoid too high and continuous water stress. Typically, a pre-sowing irrigation gift to ensure starting conditions could be applied. It may be possible that such a gift is arranged through flooding, either arranged or natural. Although I will not pursue this now, such agricultural water management might have been typical for Bronze Age agriculture in the Zerqa triangle. Furthermore, the first gift after sowing should not be too soon, as this could damage the young plants. Periods between gifts would be in terms of weeks, not days. A scenario developed in Aquacrop, in which a wheat crop receives three irrigation gifts during the season, after 30, 60 and 90 days, each 75 mm, showed that unfavourable, dry starting conditions could be overcome. Wet starting conditions would still produce more crop transpiration, but dry starting conditions would not lead to problems with crop survival. These three gifts of 75 mm would be delivered within 30 days to all farmers. When we assume that water should be available to the entire area covered by the irrigation canals of figure 1, required flows can be calculated (table 1; fig. 6). With upstream canal number 1 as the largest potential irrigable area by far, and thus the limiting area, a continuous flow in the canal system of  $0.22 \text{ m}^3 / \text{s}$  would be needed during 30 days. Assuming irrigation during day and night time, as is not uncommon, this flow would allow the whole area to be irrigated in 30 days with the required 75 mm. Canals 2 (middle) and 3 (downstream), each considerably smaller than canal 1, together cover about the same area as canal 1.

As such, canal 1 would need to be operated continuously during the total irrigation period of 90 days. Canals 2 and 3, however, could be operated in at least two different ways. In one scenario, the canals could be operated at the same time. In another scenario, the canals could be operated one after the other, as their total operation time is about 30 days. This second scenario requires less total flow for the three canals together. When comparing base flow in the Zerqa river with the water demands of the two scenarios, it becomes clear that operations after each other, thus some kind of cooperation between canals 2 and 3, pays off, as the system as a whole seems to be under much less stress. Obviously, the relative positions of

**Table 1. Irrigation gift of 75 mm every 30 days**

Canal	Irrigation gift m	Estimated surface m <sup>2</sup>	Irrigation time Days	Discharge m <sup>3</sup> /s
1	0,075	7500000	30	0,22
2	0,075	2500000	10	0,22
3	0,075	5250000	21	0,22

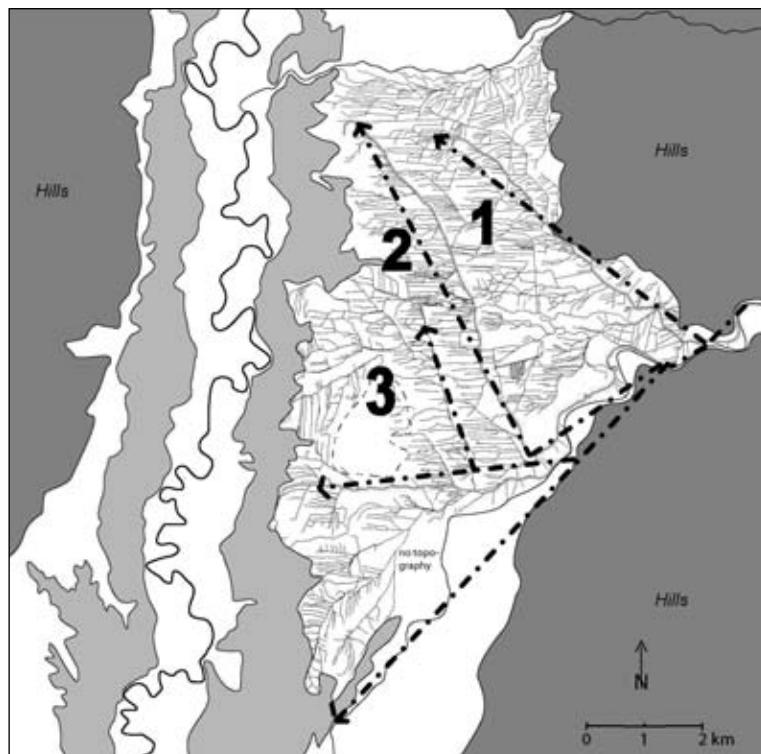


Figure 6. Simplified canal system.  
See also the full colour section in  
this book

canals 1, 2 and 3 need to be accounted for. It is clear that canal 1 as the upstream user has potentially less problems, but physical upstream positions do not necessarily coincide with social upstream positions (Ertsen & Van Nooijen 2009).

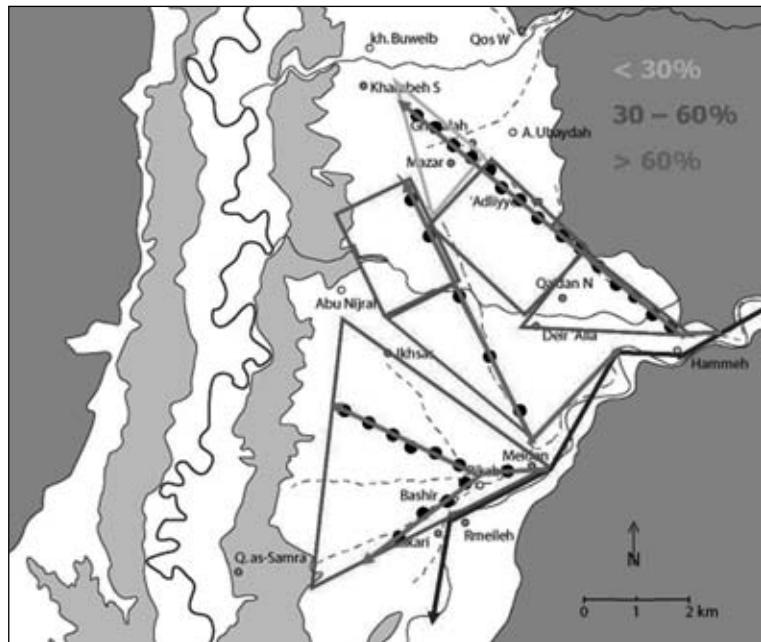
To analyse this issue of spatial dependency in irrigation further, and to include more realistic processes like river fluctuations, other types of analysis including canal modelling is needed. For example, in a study on Mesopotamia, Altaweel (2007) concluded that, amongst others, 'gravity flow irrigation' promoted stable yields. When taking a closer look, however, these calculations conceptualised this gravity flow as a 150 mm water volume in one time step. One wonders whether such water gifts could actually be delivered, as inflows would for example fluctuate. A first attempt to analyse actual water fluxes in the

same Peruvian system mentioned earlier suggested uneven distributions of flows and thus volumes over the irrigation system (Ertsen 2009). The pattern was consistent with different material remains in different parts of the irrigated the area, and could be associated with differences in water availability and management practices (Hayashida 2006).

To include this complexity from the irrigation-management perspective in the Zerqa triangle, a canal model was developed using the software package SOBEK. First, each main canal detected on the base map (fig. 1) was simplified (fig. 6). Each of the three canal areas was further simplified by equipping the main canal with offtakes each irrigating sub-areas of 50 hectares. This yielded fifteen offtakes along canal 1, five along canal 2 and ten along canal 3. Given the length of the canals, the distances between these model offtakes were different for each canal area. Canal cross-sections and slopes were based on data available on the 20th-century situation. With this model set-up, different scenarios were tested, including starting irrigation upstream or downstream, including infiltration, gate settings, etc. For each scenario it was calculated how much water would enter each 50 hectare sub-area during the 30-day interval. The total volume delivered to each sub-area was compared to the reference volume shown in Table 1. As it is unknown what management was applied in the Zerqa triangle, the relative certainty of water delivery to each sub-area, defined as the average amount of water arriving in a sub-area for all scenarios compared to the reference amount expressed in a percentage, was plotted on the canal map.

The canal system included in the model was based upon the canals from the 20th century. As such, results cannot be used directly for other periods. Especially the Mamluk period, with its irrigation of sugar cane and the need to divert water to the mills, will need a different treatment in terms of hydraulics. In figure 7, the relative certainty mentioned above is shown as an overlay to the Iron Age settlement map. As was to be expected, the upstream areas of the main canals have a more reliable water delivery than the downstream areas. Canal 3 is an interesting case, as the entire area appears to have a relatively high water

Figure 7. Relative certainty of water delivery. See also the full colour section in this book



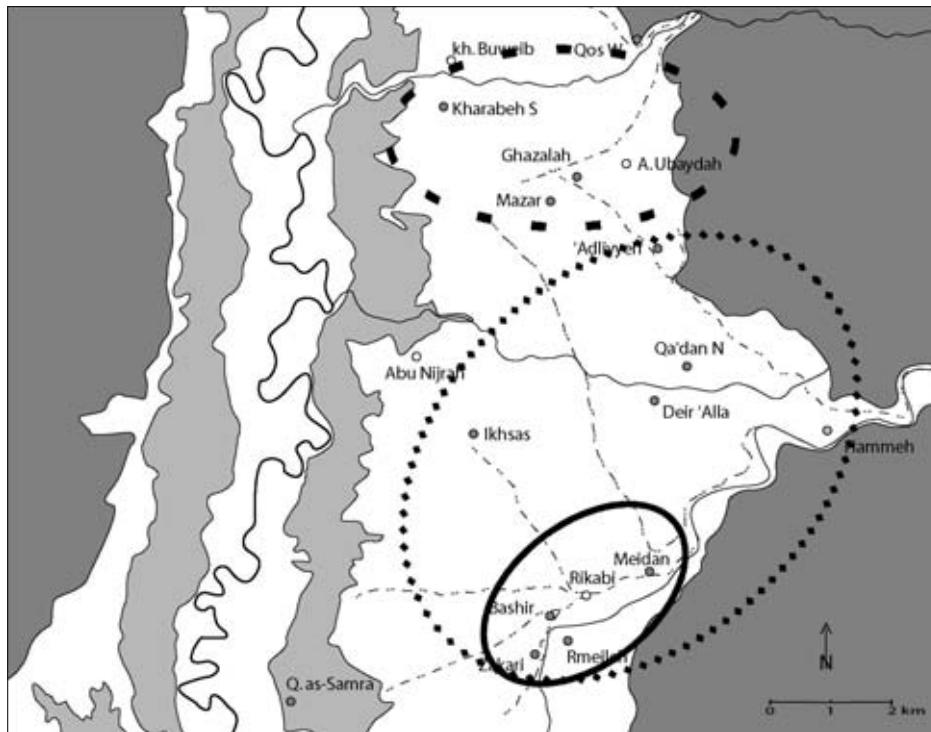


Figure 8. Linking water security to settlement.

security, even though the area is downstream of the other two. When one simplifies figure 7 into likely areas of influence of the three main canals together in relation to Iron Age settlements (fig. 8), it becomes apparent that the area in the grey circle must have been able to draw water from the canals to the north of the system in the Zerqa triangle. Furthermore, where the red area would represent a relatively certain area of influence of Zerqa water, the blue area may be the most interesting. In this area, which roughly coincides with canal 3, many settlements were found. Although these are close to the river, and as such not necessarily linked to canal irrigation, the settlements come awfully close to the canals projected on the Iron Age map. Is this a construct of my approach or an indication of the relative water security brought to these settlements through canal-based irrigation?

### FIRST CONCLUSIONS AND OUTLOOK

The calculations and modelling discussed above are still relatively simple. However, I think I have shown that it is worthwhile to develop such a modelling-based approach to generate the fluxes and balances in ancient irrigated environments, as it can yield new insights in these environments. The modelling results for the Zerqa area indicated that rain-fed irrigation would have been possible, in the case that starting conditions for the crops would be favourable. Furthermore, it was shown that irrigation in the growing season could overcome dry starting conditions. In both cases, irrigation would have been needed, but could result in quite different management arrangements. However, in all irrigation management arrangements, sharing the water from the river would have been an issue. The model results suggest that cooperation between users of the different canals would have been more beneficial than conflictual.

These conclusions need to be taken with care. A fundamental aspect of the modelling methodology is that the reference situation is unknown, which in my view demands modelling approaches explicitly based on the physical processes creating surface and subsurface water fluxes. A recent initiative of the International Association of Hydrological Sciences, Predicting in Ungauged Basins (PUB), shows the strength of new, largely understanding-based methods instead of calibration-based methods. PUB aims to improve existing hydrological models in terms of their ability to predict in ungauged basins, with a focus on predictive uncertainty, alternative data sources and the links between these two issues (Sivapalan et al. 2003). It is true that simple, conceptual models do allow for quick analysis of water systems. Simple models, however, cannot provide the detailed analysis of the material context for irrigation needed in this research, precisely because there is no information to validate the models of ancient irrigation systems. The drawback of using conceptual models is their inherent uncertainty in the values for the model parameters, which are not based on realistic physical behaviour. These model parameters need to be calibrated against real data, which are not available. Applying conceptual models only will increase the uncertainty of model outcomes. Compare the irrigated landscape with a bath tub, for which we can establish physical properties and set realistic filling and emptying mechanisms, including a shower (rainfall), tap (river) or leak (groundwater) – compare with Harrower (2008) who used a digital elevation model (the bath tub) to define the channels when analysing irrigation in Arabia. Setting parameters in such a model requires good quality data on aspects like soils, climate, geology and groundwater. Applying physically based models can yield realistic results, even in catchments without measured data (Lange et al. 1999, as margins of uncertainty of the physical parameters are being constrained by nature).

## **ACKNOWLEDGEMENTS**

I am extremely thankful to Eva Kaptijn for the discussions leading to this paper and allowing me to use her basic material (which I partially helped to develop). We presented part of the material in the session on 'Responses of Complex Societies to Climatic Variation' at the Stine Rossel Memorial Conference, Climate and Ancient Societies: Causes and Human Responses. Other elements were developed during the workshop on Water and Power, University of Durham, UK, organised by Tony Wilkinson.

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