Analysis of the hydraulics of the irrigation canals of Otrar, Kazakhstan

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ABSTRACT

Surveys of relic canals at the Oasis of Otrar in Kazakhstan have been used to re-construct patterns of agricultural water use for irrigation between AD700 and AD1500. Hydraulic simulation software was used to calculate the water carrying capacity of historical irrigation canal networks. An analysis of modern day irrigation systems has enabled the calibration of crop water use models and an estimate of the effectiveness of the ancient irrigation canals was made. The hydraulic models show that significant organisation of the management of the canals was necessary to ensure correct delivery of water to the farms.

Key words | archaeology, Central Asia, hydraulics, irrigation

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INTRODUCTION

Significant organised irrigation has been practiced in Central Asia along the rivers Amu Darya and Syr Darya for over 1,300 years. Groshev (1986, 1987) discovered remnants of irrigation works in this region along the middle and lower reaches of the rivers Syr Darya, Talas and Chu, starting as long ago as the 5th Century BC. Otrar is located on the middle Syr Darya river (42°42′N, 68°10′E, Figure 1). This rich complex of channels, oxbow lakes and shifting floodplains formed the site of the Oasis of Otrar, a key settlement in Central Asia on one of the routes of the Silk Road.

The region is still being used for crop production and following the introduction of large-scale irrigation systems in the 1950s and 1960s has caused well known problems including over-abstraction of water from rivers, inefficient irrigation, salinisation of agricultural lands, reduced inflows into the Aral Sea and the associated problems of desertification (Micklin 1998; Tanton & Heaven 1999; Murray-Rust 2003). The aim of this study was to explore the pattern of development of the irrigation canal networks in the Oasis of Otrar and use modern irrigation and hydraulic design software to quantitatively assess the way in which the canal systems were managed and operated.

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The Oasis of Otrar

The Oasis of Otrar is sited in the valley of the Syr Darya River near its confluence with the River Arys, The valley floor consists of former meanders developed when the river Syr Darya was much larger and active, fed by snow melt in the Tien Shan mountains in Kyrgyzstan. The present main course of the river Syr Darya formed during the Late Pleistocene. During the Holocene, large floods created numerous deposits and the river meandered across a zone 30–60 km wide. The river changed position regularly, resulting in a region of shallow terraces with deposits of silts sands and clays overlying an extensive gravel aquifer. Annual floods would replenish large areas of the Otrar Oasis aquifer and provided a useful natural irrigation that was exploited by constructing water storage areas in former oxbow lakes. Summer discharges have progressively decreased due to the retreat of the ice deposits in the Tien Shan mountains with a more significant decrease during the last 1,500 years.

The Oasis of Otrar covers an area of approximately 20 km × 20 km and consists of low lying land near that has provided settlers with opportunities for organized large

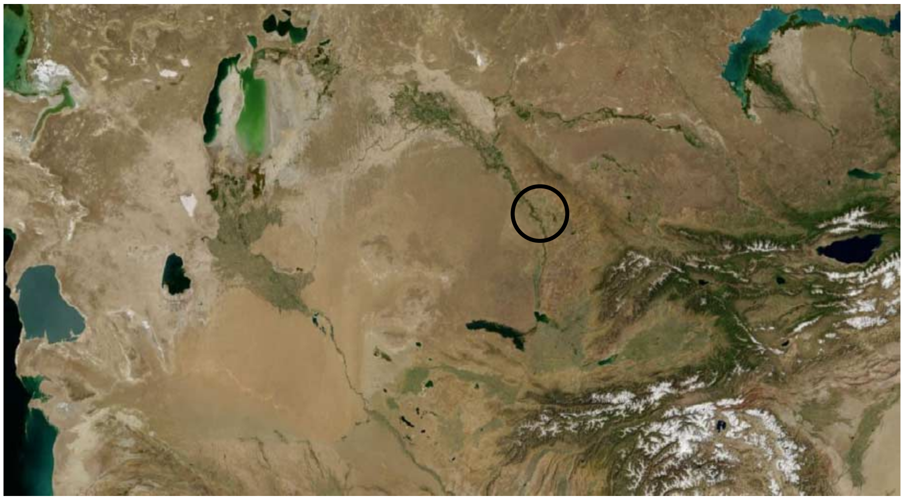

Figure 1 | Location map of Otrar Oasis in Southern Kazakhstan.

scale irrigation. The old canal routes through the area are still visible both on the ground and in the air together with evidence of 10 large walled towns and 50 small villages. The main town of Otrar (estimated maximum population 30,000) was one of the most powerful urban centres of the Silk Road, and formed a bridge between trading, farming and pastoralist cultures. It was a fortified mediaeval town located near the junction of the River Syr Darya and its tributary the River Arys (UNESCO 2005, 2009*a*,*b*). Remnants of the town still exist as a 20 m high raised earth platform (or "tobe") 500 m across that provided protection against floods and attacks (Figure 2).

Other smaller satellite settlements were spaced at approximately 5 km intervals and each were supplied by earth canals fed from the Arys or Syr Darya Rivers (Figure 3).

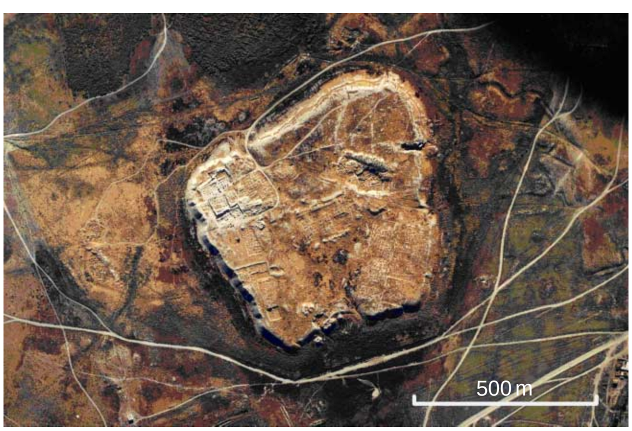

Figure 2 | Otrar city.

METHODOLOGY

Data on the irrigation works of the Otrar Oasis were collected by aerial, field and desk studies and are described in detail by Aubekerov *et al.* (2003). The layout of water movement systems (canals, locations of river offtakes and water storage areas) were mapped and a survey of the cross sections of the main canals in the systems was made.

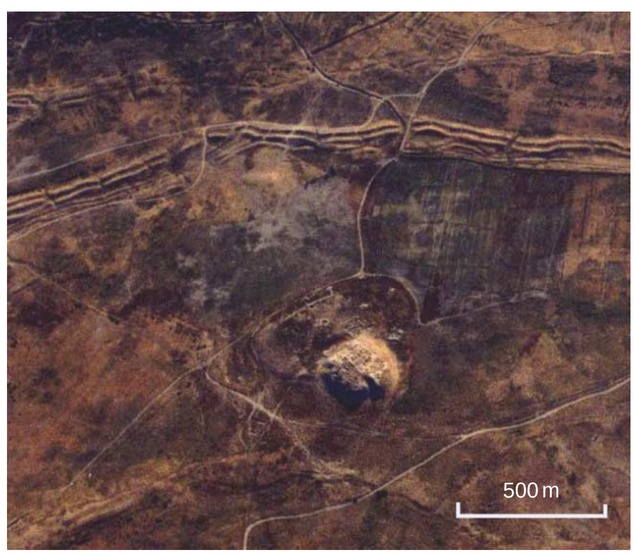

Figure 3 | Irrigation canal and small township.

The age of the canals was determined through a series of excavations which enabled dating using distinctive pottery remains. Additionally several hearth sites have been used for C^{14} dating and palynological analyses of grains near the fires provided information on crops likely to have been cultivated in the region.

Stages of development of the Otrar Oasis canal network

The reconstructed pattern of irrigation channels derived from the field work showing the history development of the irrigation network is summarised in Figure 4 (after Clarke *et al.* 2005). Before 500 BC there is evidence of dispersed irrigation in the area but no organised system is apparent. A network of channels that formed the diffuse delta of the Rivers Arys and Bogun where they joined the various pathways of the main Syr Darya river is shown in Figure 4(A).

Between 500 BC and 500 AD, irrigation systems developed on flood plains and deltas of rivers. Communities in walled villages stored seasonal floodwaters in natural depressions such as ox-bow lakes to maintain ground water and to enhance soil moisture. On higher ground there is evidence of water harvesting using ditches filled with rocks, suggesting that the period was relatively wet (Figure 4(B)).

From 800 to 1300 AD the northern territories of Central Asia came under Turkic rule, characterised by expansion onto the floodplains and deltas, where agricultural communities implemented large collective works under centralised organisation and proto-towns. The canal networks were connected to the Arys River and as the area grew,

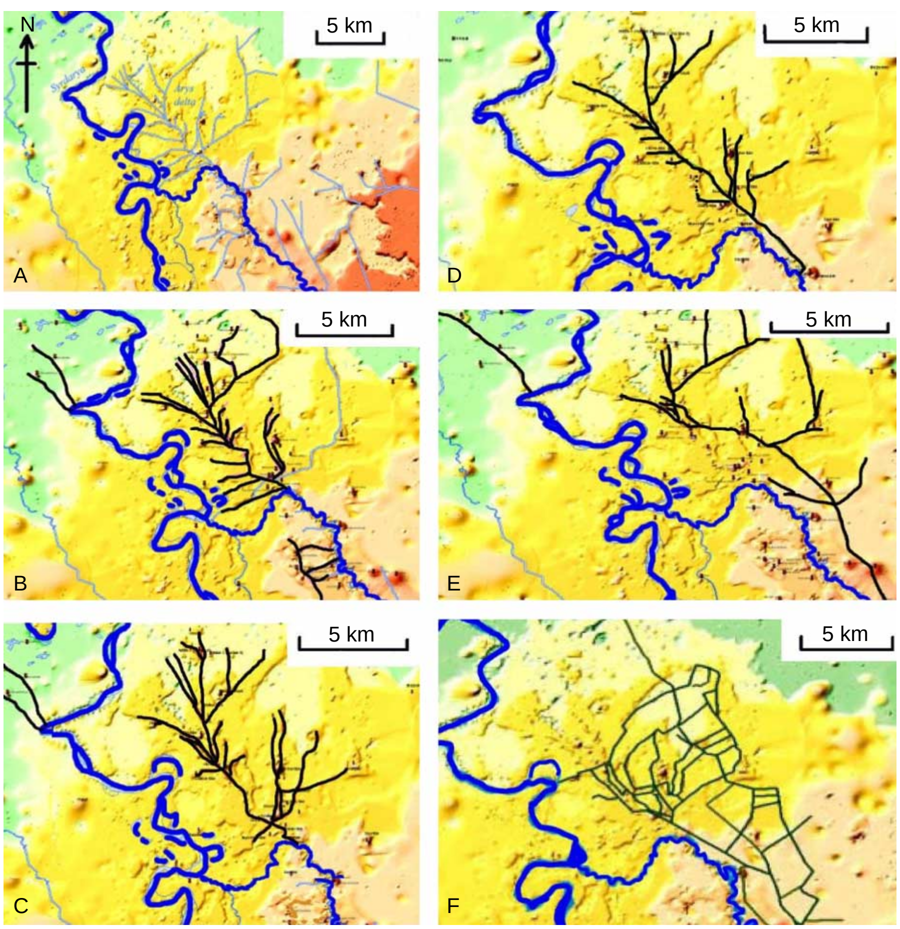

Figure 4 | Development of irrigation canal network at the Otrar Oasis (Clarke *et al.* 2005).

it was necessary to re-locate the offtake from the river to the canal further upstream to permit canals to supply water over larger areas of land (Figure 5).

Between 1400–1500 AD, irrigation became more organised and the offtake from the River Arys was moved 10–12 km upstream (Figure 4(C,D)). The irrigation systems were characterised by canals 5–10 m wide and 10–30 km long. This complex system required cooperative or centralised organisation and management of water delivery. This was a surplus-producing agricultural society, with commercial networks ruled by well-organised statehood, feeding a large system of fields and several towns and villages.

During 1600–1700 AD the irrigation canal offtake was moved a further 15 km upstream, providing hydraulic command over a larger area to the north of Otrar. At the same time the regions in the south and western part of the oasis stopped cultivation, probably due to the accumulation of salts in the soils after many centuries of irrigation (Figure 4(E)).

In the 17–18th centuries the irrigation system collapsed, water control structures were abandoned and agricultural production decreased. The population declined and the region became dominated by nomadic herdsmen. The modern irrigation system was established in the 1920's when a cross weir was constructed in the River Arys 25 km upstream of the town of Shaulder. The main irrigation canals were lined with concrete and initially the system was capable of carrying 8.9 m^3/s of water. A series of deep drainage channels were added to the project starting in the 1950s to remove surplus water, control water table levels and salt accumulation in the soil (Figure 4(F)). The project was expanded in the 1970's by widening the main canal to a capacity of 12–15 m^3/s.

Estimating canal capacity and irrigated areas of the ancient irrigation systems

The dimensions of the main and secondary supply canals (bed width, side slope, bed slope and berm width) were surveyed at key locations along the identified ancient canal networks. These data were used to reconstruct trapezoidal canal cross sections which could be built by hand using the unconsolidated silt sediments of the region. The slopes of the channels were surveyed and checked from topographic maps. This provided sufficient data to calculate the probable maximum water carrying capacity of each of the surveyed canal sections using Manning's equation using typical values of roughness coefficient (Figure 6).

The calculations provided estimates of how much water could be conveyed in different parts of the former irrigation canal networks. However the capacity of any one canal in the system depends on the amount of water entering it from upstream canals and therefore it was necessary to consider the each network of canals as a complete hydraulic system rather than a set of individual sections.

The oldest canals fed the irrigated areas nearest to the river and had a low water carrying capacity, typically 2–4 m^3/s. Over time these canals were widened and deepened to transport more water to areas further away

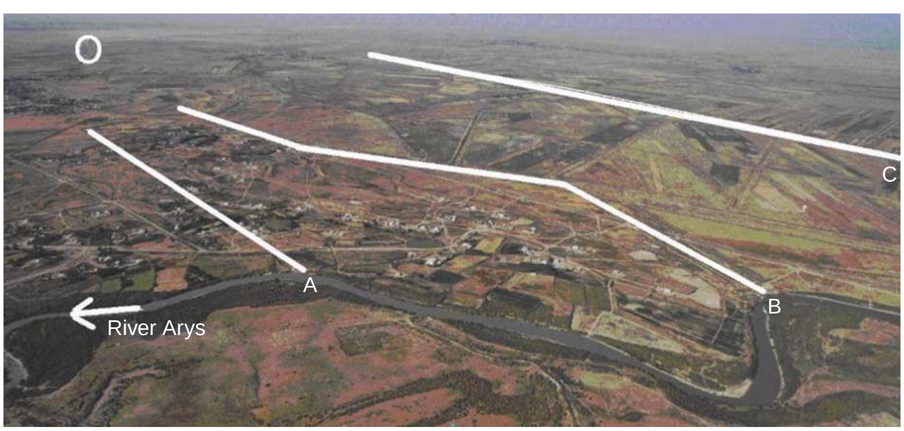

Figure 5 | Progressive relocation of canal offtakes from the River Arys. A, B, C refer to stages of development in Figure 4. O=site of Otrar.

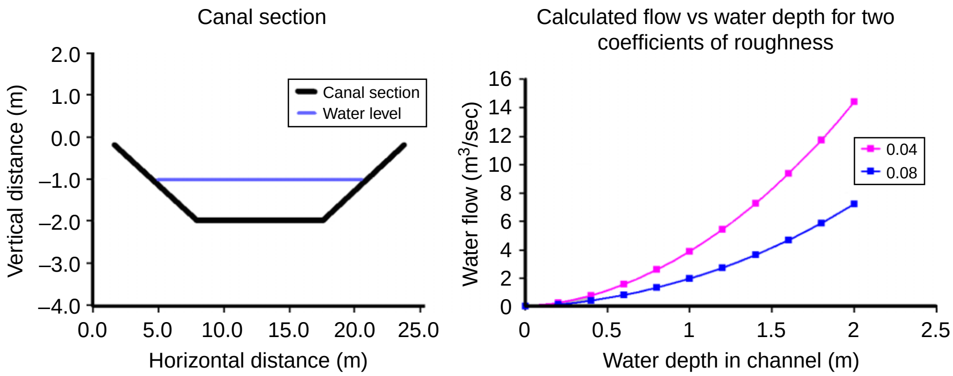

Figure 6 | Use of canal cross section data to estimate water carrying capacity using Manning's equation.

from the river offtake. Typically the 6th Century canals reached areas up to 15 km from the river, and 9th Century canals were up to 20 km long. The 15th Century and modern irrigation canals extend more than 30 km from the river Arys.

At the sites where the main irrigation canals were connected to the river Arys, canal cross sections are large and Manning's equation suggests that the canal flow capacity was around 20–50 m^3/s. This is much greater than the modern average annual river flow of 15–25 m^3/s and suggests that the main channels were either used as storage channels, or that they were used to capture springtime flood flows for use in spate irrigation.

There are no written records of how the ancient canal systems were managed and operated. It is likely that the main canal was used to deliver water under some central control and secondary canals were then used to deliver water to sub-areas. This is illustrated by a noticeable canal feature at Altyn where there is a significant junction of many canals (Figures 7 and 8). The canals have been re-built several times on former canals, but there are no relics of water control structures remaining. It is not known if the water was simply split between farms at this site or if it was managed using gates or chokes to deliver water to differing areas at differing times.

Hydraulic analysis of the canal networks

To evaluate the performance of the various canal networks, a series of hydraulic models was constructed using the

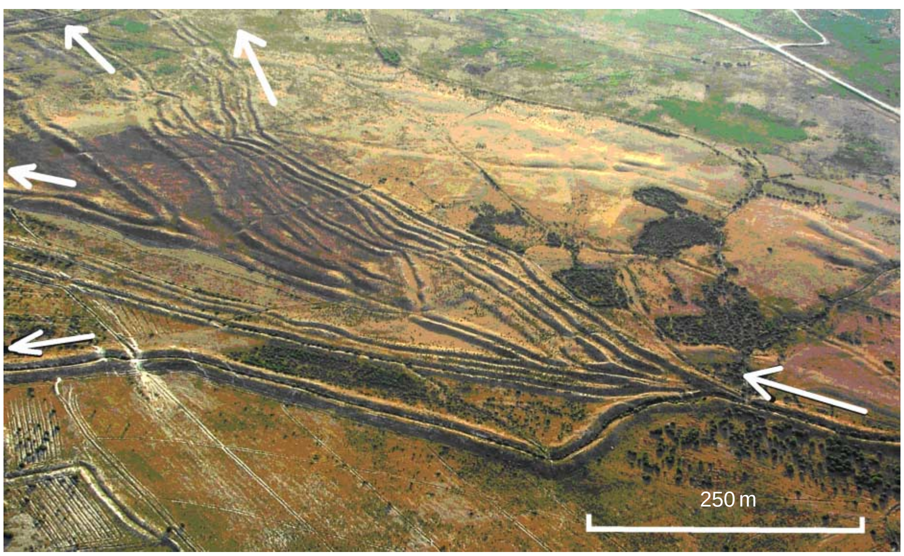

Figure 7 | The "Altyn Knot" a key water distribution junction, showing how water could be allocated to differing parts of the oasis.

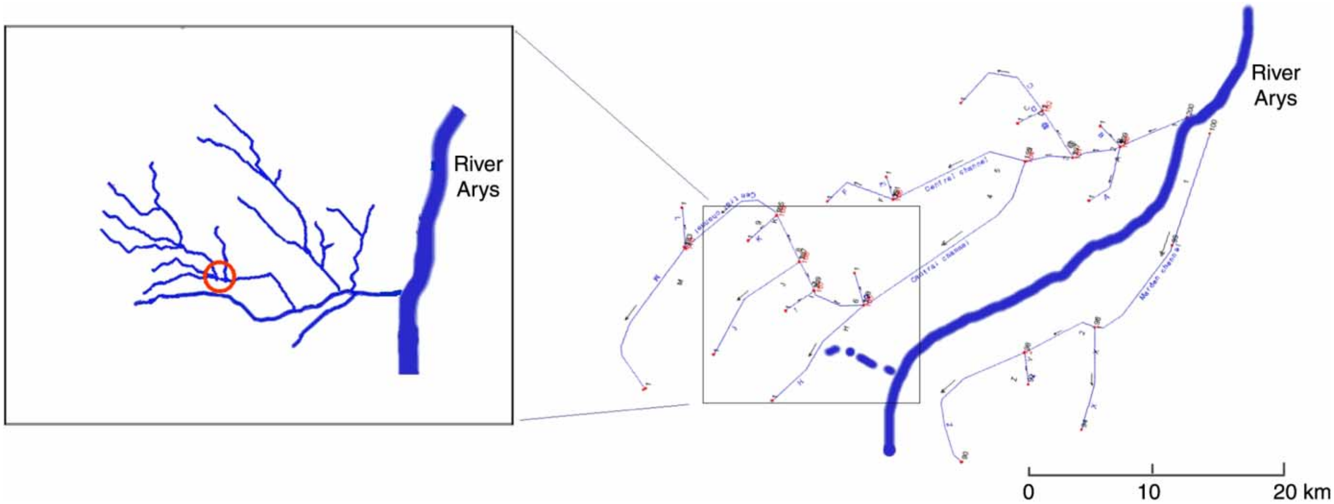

Figure 8 | HEC RAS model of the 12th century system (left) in relation to the modern day canal network (right). Broken line indicates original offtake from the river into the canal network. Circle shows location of the "Altyn Knot".

US Corps of Engineers River Analysis System software (HEC-RAS 2009). These models represented the network of the main and secondary canals together with some representative tertiary canals. Estimated average spring and summer river flows from the River Arys were numerically routed through the canal systems to investigate the performance of the canal network. A key aim was to determine whether the canal networks were able to supply all of the canals simultaneously or if it was necessary to create schedule of rotating water delivery through different canals on different days. Figure 8 shows the layout of the 12th Century canal system, together with its location in the modern day canal network, where the offtake is further up the river.

The initial hydraulic models were run by assuming an inflow of water of 6–8 m^3/s and there were no control structures active, allowing water to flow into every canal in the system. Results (Figure 9) suggest that the water distribution in this situation was very unequal. Some canals were adequately filled (A), some received too much water (B) and overflowed and other canals barely filled at all (C).

These results suggest that the canal system could not be operated with all canals open at the same time. The models were re-run with a rotation of water delivery from the main canal to each of the secondary canals in turn with (Figure 10). The revised model indicated that rotational allocation enabled water to be transported with adequate capacity along 70–80% of each of the secondary canal's length. The remaining 20–30% of the canal's length would receive any remaining water. As a result the agricultural production at the "tail end" of these canals would have been limited by water deficit. These findings indicate that water managers were probably a necessary part of society and they decided when to divert water to differing canals. This suggests that a high level of social and technical organisiation probably existed in the Oasis, as water distribution required cooperation between the various townships in the area.

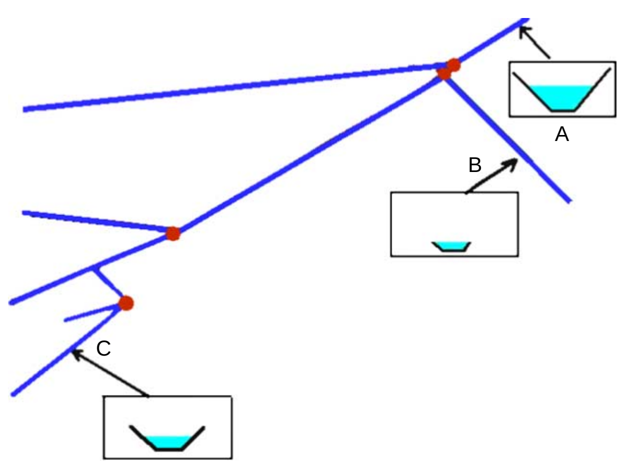

Figure 9 | Simulation of 12th century water distribution system with no control gates. A=main canal input, B=small canal over flowing, C=large canal receiving too little water.

Operation of the modern irrigation system

To evaluate the effectiveness of the above findings, the modern irrigation canal system (see Figure 11) was modeled using HEC-RAS. Meetings with the managers of the modern irrigation system provided data that enabled the calculation of the crop water requirements for the present day crops (cotton, maize, sunflowers and vegetable). Soil data for the region (grain structure, water holding capacity) were available from Turkestan, a similar Oasis to the north studied by INCO COPERNICUS Project "Cropsal" (Clarke 2001). These data were used to create an irrigation planning model for the modern irrigation system based on the United Nations FAO "CROPWAT" software (Clarke *et al.* 1998). The model estimated crop water requirements in mm/day using climate data (temperature, humidity, sunshine and wind speed) using the Penman-Montieth equation.

Irrigation water requirements were calculated using effective rainfall, simulation of soil moisture deficit and the calculation of the timing and amount of irrigation water needed to maintain a healthy crop. Peak irrigation water requirements we calculated as 7.64 mm/day, equivalent to a continuous canal flow of 0.88 l/s for each hectare of crop at the peak of the growing season.

This peak flow value was used to estimate the dimensions of the canals. Local information indicated that canal leakage and in field water losses means that only 50% of the water taken from the river was effectively delivered into the root zone of the irrigated crops. Hence managers aimed to supply up to 1.76l/s/ha to the crops. Assuming that the main irrigation supply canal extracted 10 m^3/s from the river Arys, it would be possible to fully supply 5,500–6,000 hectares of land at 1.76 l/s/ha, assuming an overall efficiency of 50%. This is notably lower than the planned area of 10,000 ha. The discrepancy between planned and actual areas is a result of poor system efficiency caused by lack of maintenance to the concrete lining of canals and gate structures being poorly operated.

The HEC RAS water delivery simulation agreed well with the performance of the current system, where the tail ends of the irrigation canals received little water and have reduced productivity, which is the same as the findings from the results of modeling the ancient irrigation systems.

Another important observation is the presence of salts in the irrigated soils, especially in the southern parts of the modern irrigation system. This mirrors the development of the ancient irrigation networks, where farms closest to the river and in the lowest lying areas were progressively abandoned and farming moved onto slightly higher land.

This information is useful in understanding how the ancient canal networks would have been managed. The modern main irrigation canals are lined with concrete, but the more distant farm canals are not. The ancient canal networks would probably leak 50–70% of the water taken from the river. These losses mean that the more remote parts of the network would not receive enough water except in very wet years. However the water that leaked from canals may have been used beneficially; farmers would almost certainly have taken advantage of wetlands created by the lost water. Unfortunately over the long term,

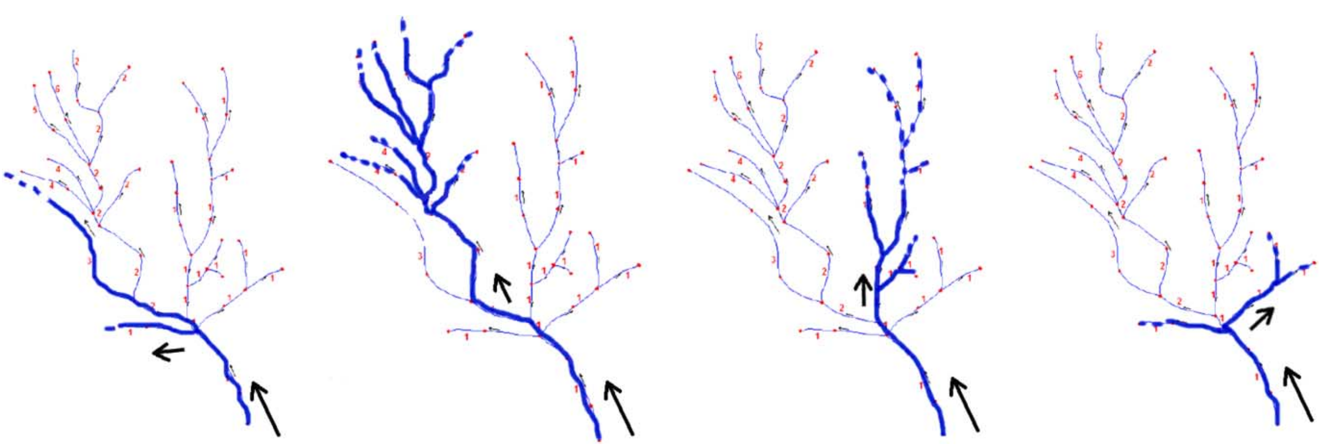

Figure 10 | Example of rotational irrigation along secondary canals: dotted sections indicate inadequate water supply at end of canals.

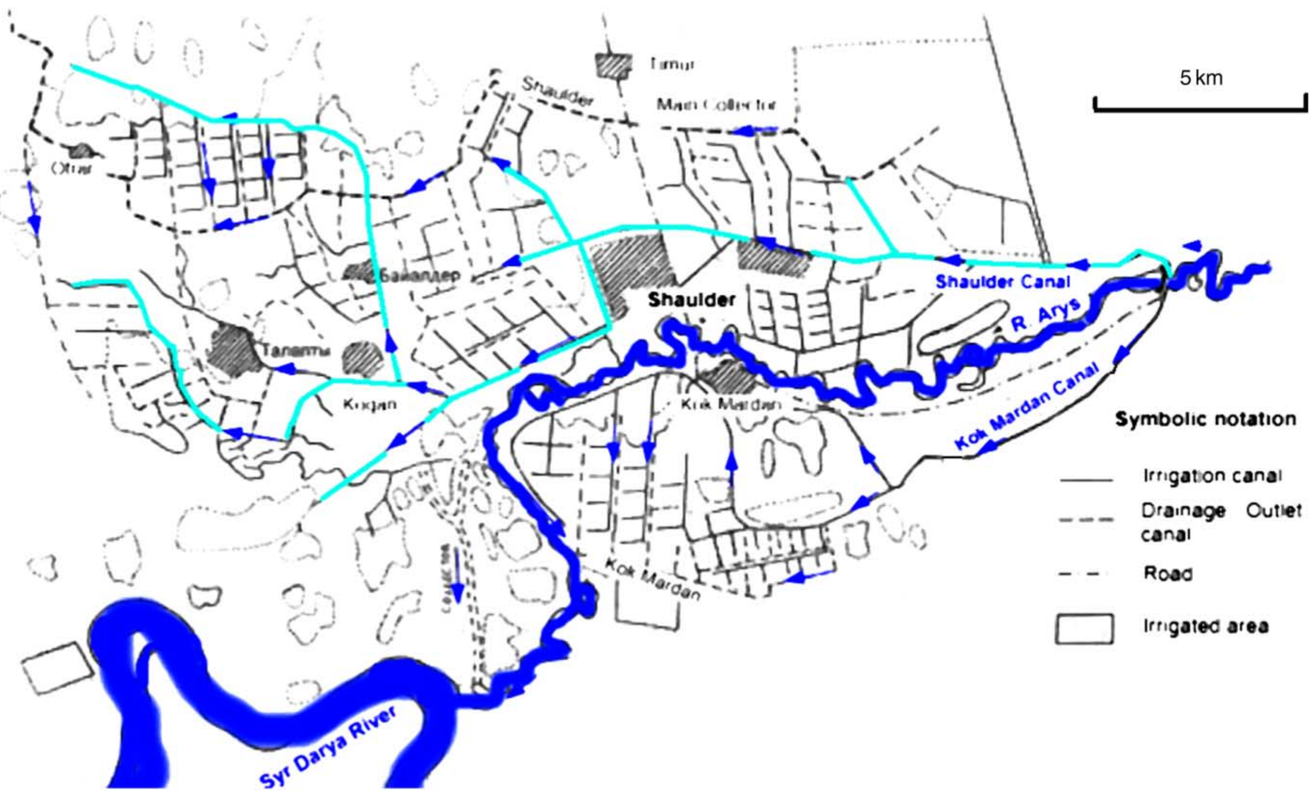

Figure 11 | Modern irrigation system layout.

this would result in high evaporation rates from some areas of the Oasis. The evaporated water would leave small mineral traces which would build up over a period of 100–200 years and slowly contaminate the soil. As a result, farms in the lowest lying areas would slowly be abandoned. This process is evident in the history of the canal network development (Figure 4), which shows a gradual movement of the canals northwards away from the Syr Darya river. This explains why the canal offtake was moved upstream to give control over the new areas which were at a higher elevation than the abandoned farms.

CONCLUSIONS

This work has shown how crop water requirements calculations combined with modern hydraulic software, which is normally used for design of river flood embankments, can be used to understand the operation of ancient canal networks.

From the work described here it was possible to gain a technical insight in to how the irrigation system at the Oasis of Otrar developed. Key issues identified included the need for cooperative management and operation of the canal system to ensure adequate delivery of irrigation water to each area of the Oasis, the need to gradually move away from the poorly drained lowland areas closest to the rivers where salt accumulation reduced the soil fertility, and the progressive re-location of the main canal offtake further upstream to provide additional water command over higher level land and permitting the irrigating a larger area of crops.

In the analysis presented, the flow rates in the canals had to be estimated, but using modern design software such as CROPWAT it was possible to calculate the amount of water required to grow each hectare of crop, and hence calculate the water flow in the canals to grow the crops. This software should become a valuable tool for all scientists interested in the irrigation practices on ancient cultures.

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