Reconstructing irrigation at Otrar Oasis, Kazakhstan 800-1700AD

D. Clarke, R. Sala, J. Deom, E. Meseth

Abstract

Irrigation has been practised near the Syr Darya river in Central Asia for over 1300 years. Low-level aerial surveys have been used to determine the extent of the former canal network and archaeological excavations have identified phases of expansion and contraction of towns that depended on irrigated agriculture. From AD 1000 onwards, extensive series of engineered canals were constructed, producing a rich agricultural society in a region formerly considered to be dominated by nomadic pastoralists. Phases and expansion of agricultural development are related to regional changes in climate. Modern irrigation models have been used to reconstruct likely crop water requirements.

Key words: Irrigation, Central Asia, Archaeology

Introduction

Water resource management in Central Asia faces many challenges at present, 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 (Tanton and Heaven,1999). Many of these problems stem from the introduction of large-scale irrigation systems in the 1950s and 1960s, diverting water from the Rivers Amu Darya and Syr Darya.

Despite the commonly held belief that the region was previously dominated by nomadic herdsmen and traders traversing the Silk Road to China, significant organised irrigation has been practiced in this area for over 1300 years. Groshev (1986,1987) discovered remnants of irrigation works in the middle and lower reaches of the rivers Syr Darya, Talas and Chu, starting as long ago as 500BC.

Low-level aerial surveys were used to identify networks of earth irrigation canals leading from the Rivers Syr Darya and Arys into the steppes of central Kazakhstan. Information on these irrigation systems was then correlated with archaeological data on settlements. A cyclical series of expansion of towns followed by collapse have occurred, and these cycles have been related to political upheaval and patterns of climatic variation. A study of the modern day irrigation systems has enabled the calibration of a crop water requirements model that is used to describe the scale of the water distribution network and to confirm the likely extent of irrigated agriculture in the past.

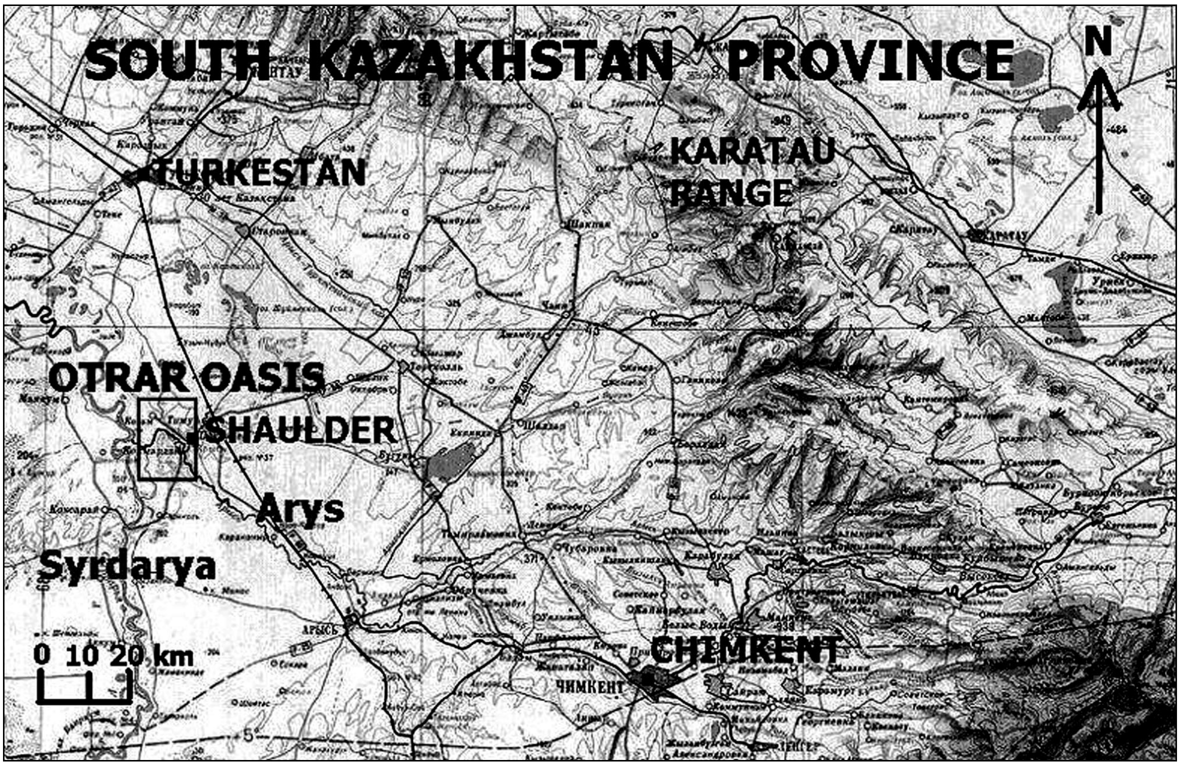

Fig 1: Location map of Otrar Oasis in Southern Kazakhstan.

Physical Setting

The Otrar oasis (42°42'N, 68°10'E) is located on the middle Syr Darya river near the confluence with the Arys river (Fig 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. Jansen (2002-2003) quotes the soviet archaeologist Bernshtam: "It is really hard to find a more advantageous and more perilous site in the whole of Central Asia than that of Otrar".

The valley floor consists of meanders developed when the Syr Darya river 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. Historically, the path of the river changed continuously. This has resulted in a region of shallow terraces with deposits of silts sands and clays overlying an extensive gravel aquifer.

Annual flood waters would cover large areas of the Otrar Oasis and provided a useful natural irrigation that was exploited by constructing water storages in former oxbow lakes. In the northern part of the Otrar oasis a 20km long relic secondary course is preserved 5 km north the main river bed. This course is hydraulically connected to the Syr Darya via the underlying gravel aquifer and is often filled by out of bank flood waters. Summer discharges have progressively decreased due to the retreat of the ice deposits on the Tien Shan mountains with a more significant decrease during the last 1500 years.

In 1964 the Chardara reservoir was constructed to store and regulate water of the

Syr Darya. Extensive irrigation systems were constructed to make the former Soviet Union self-sufficient in cotton. This large-scale reservoir development in the last century resulted in control of river flows and with the extensive abstractions of water for irrigation has led to the well-known shrinkage in the volume of the Aral Sea.

The modern climate of the Otrar oasis is classified as dry semiarid continental. Average summer temperatures rise to 35°C and winter minima of -10°C. Average annual precipitation in the last 50 years is 213 mm, falling mainly in January-March. Potential evapotranspiration calculated using the Penman Montieth equation is 1350 mm/year, although severe soil moisture deficit limits actual evapotranspiration to under 150 mm/year on unirrigated areas and 730mm/year for typical modern field crops. Present day irrigation consists of a mixture of crops - cotton, maize, sunflowers and vegetables; (Tugelbaev, 2003) and is grown on the site of former irrigation works, leaving a complex series of modern and ancient channels crossing the area.

Human Settlement Patterns in the Otrar Oasis

Remnants of the former Otrar covers an area of 200 km^2 with evidence of 10 large walled towns and 50 small villages. The main town of Otrar 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, 2004). The nearest modern town is Shaulder located 20km to the south, on the River Arys.

Otrar City remains as a 170ha platform (or "tobe") of earth, 20m high that provided protection against floods and attacks (Fig 2). Other smaller satellite settlements were spaced at approximately 5km intervals and each were supplied by earth canals fed from the Arys or Syr Darya Rivers (Fig 3).

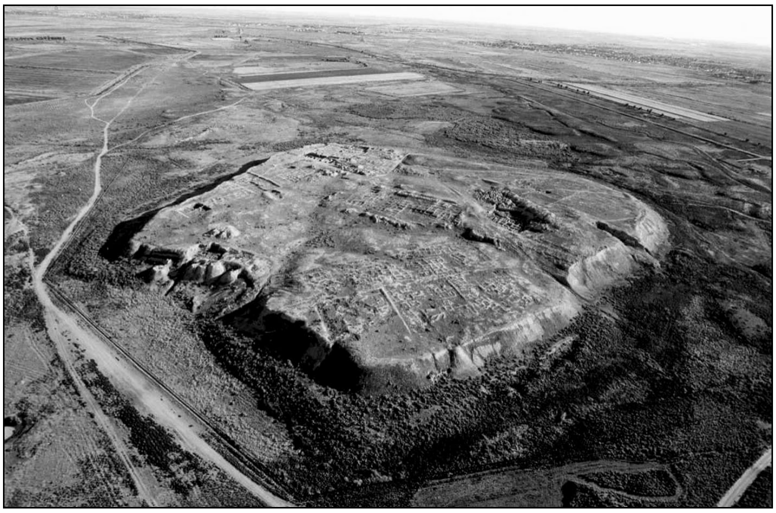

Fig 2: Town of Otrar on raised "tobe".

Fig 3: Altyn-tobe, supply canal.

Fig 4: Air photo of 12th Century irrigation canals at Altyn Fork.

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). Satellite imagery and low level air photography were used to determine the location and extent of former irrigation channels which are often invisible at ground level (Fig. 4).

Settlement patterns and the layout of water management systems were determined by mapping canals and various types of water storage systems. The system of canals and fields provides the basis for explaining settlement sites. The location of river off takes and the network of supply canals has been mapped and the dimensions of the remnants of the major canals in the network have been surveyed. A systematic reconstruction of the irrigation system and the field-crop system is currently under development.

Excavations in a range of typical settlements have enabled dating of key stages of agricultural expansion. Each period of economic activity is identified by abundant and distinctive pottery remains. Numerous hearth sites have been used for C^{14} dating and palinological analyses of grains near the fires provide information on crops likely to have been cultivated in the region. These data were then compared with a reconstruction of the scenario of climatic and hydrological changes during the last 3000 years to determine the evolution of the irrigation system and of its decay before abandonment.

Stages of development of the Otrar Oasis

The reconstructed pattern of irrigation channels derived from the field work showing the history development of the irrigation network is summarised in Figure 5.

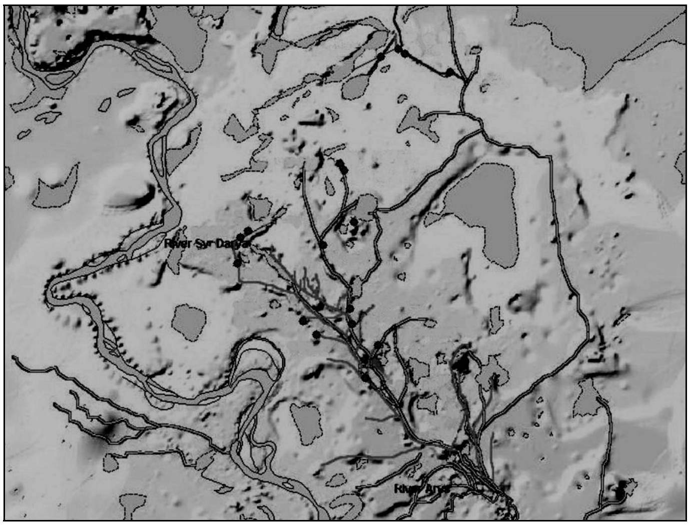

Fig. 5 A

Phase 1:
200 – 650 AD

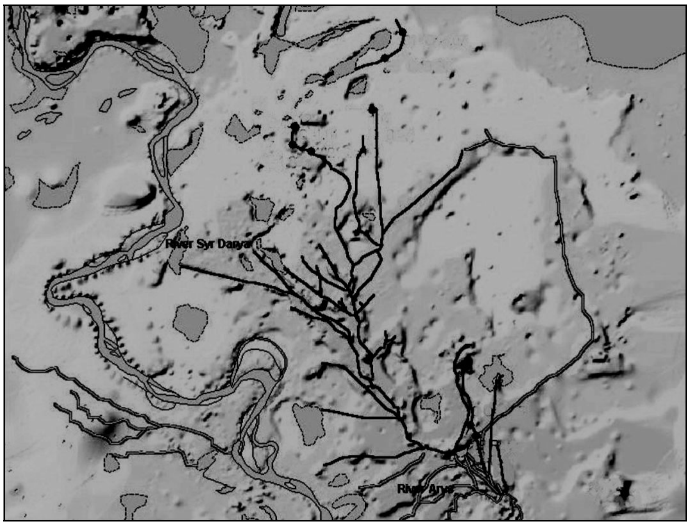

Fig. 5 B

Phase 2:
650 – 950 AD

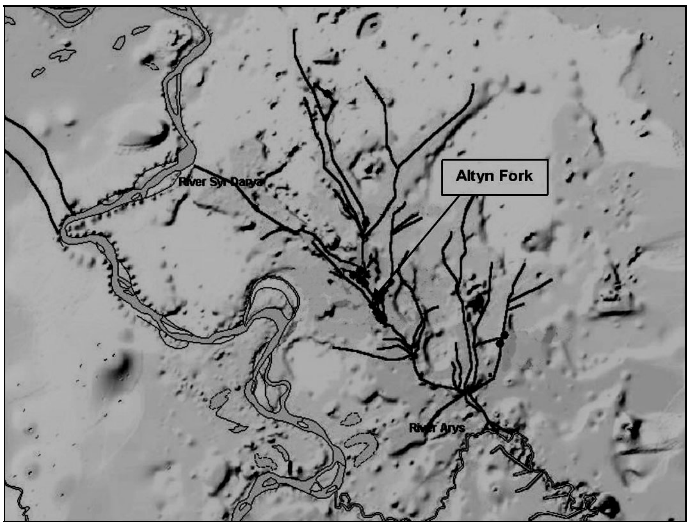

Fig. 5 C

Phase 3:
950 – 1200 AD

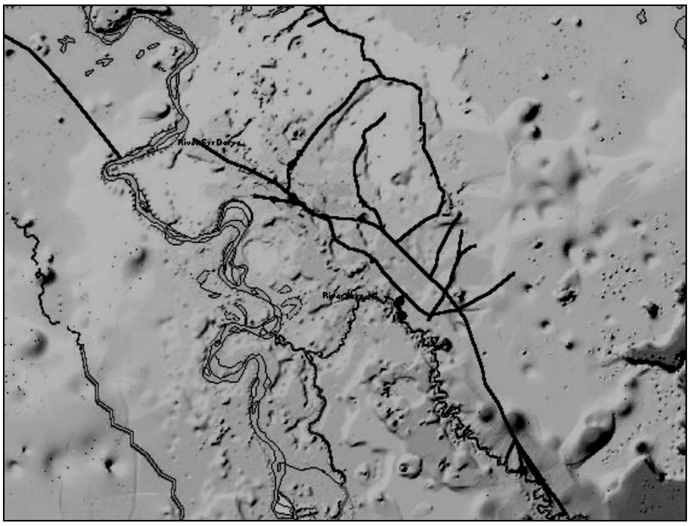

Fig. 5 D

Phase 4:
1200 - 1350 AD

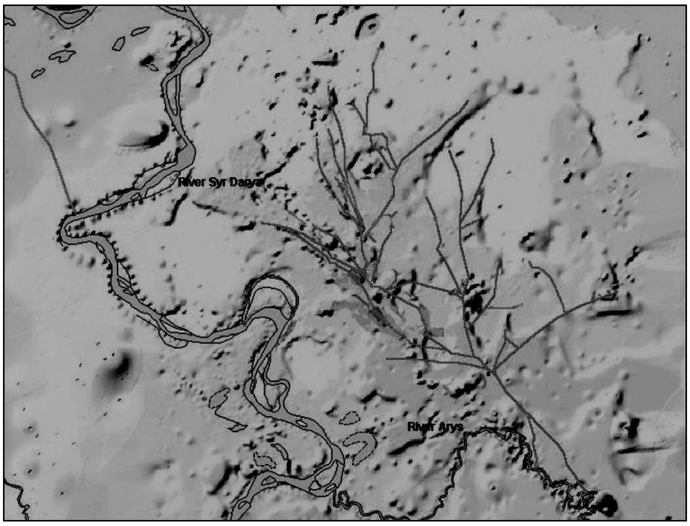

Fig. 5 E

Phase 5:
1350 - 1700 AD

Figures 5 A to 5 E:

Evolution of the river drainage and irrigation canals in the Otrar Oasis from 200 AD to 1700 AD.
Source: Sala and Deom (2004).

Phase 1. Between 200 and 650 AD there is evidence of dispersed agricultural settlings and basin irrigation in the area but no organised system is apparent. The network of natural channels and basins of the delta of the Rivers Arys and Bogun where they met the Syr Darya river were exploited (Figure 5-A). Communities in walled villages stored seasonal floodwaters in natural depressions such as ox-bow lakes to maintain ground water and enhancing the soil moisture. Primitive canals linking these depressions are found in the northern and southern parts of the oasis and are suspected to date from this period.

Phase 2. Between 650 and 950 AD, the first irrigation systems developed on flood plains proximate to secondary branches of the Arys and Bogun deltas and of the River Syr Darya. Delta distributaries were paralleled by channels, sometimes exploiting the old riverbed, to allow longitudinal distribution of water. On higher ground there is evidence of water harvesting using ditches filled with rocks, suggesting that the period was relatively wet (Figure 5-B). Groshev (1987) remarks that on this period, the first large hydraulic works were constructed, canals up to 7m wide are dug along the western distributor called Sangyl surrounded by the main towns.

Phase 3. From 950-1200 AD the northern territories of Central Asia came under Turkic rule and saw the expansion of irrigation practices onto the floodplains and deltas, where agricultural communities implemented large collective works under centralised organisation and proto-towns. Water catchments were applied to the main river course; irrigation was less extensive but more organised, the south western regions are abandoned, possibly due to salinisation. All data suggest the existence of drier conditions (Figure 5-C). The period sees the first economical and cultural blossoming of the oasis, with a surplus-producing agricultural society, with commercial networks ruled by well-organised statehood, feeding a large system of fields and several towns and villages. As describeded by Groshev (1987), a permanent reservoir was built next to the River Arys and at the head of the trunk canal.

Phase 4. The period 1200-1350 experienced cyclical changes partly due to political upheaval and partly due to climatic conditions. The offtake from the River Arys was moved 5km upstream. Expanded irrigation systems characterised by canals 5-10 m wide and 10-30 km long, with locks, basins and reservoirs, suggests a centrally planned and organised system of irrigation (Figure 5-D).

Phase 5. 1350-1700 showed another migration of the offtake, a further 13km upstream, providing hydraulic command over the northern areas (Figure 5-E). The new irrigation system together with the start of a wet climatic phase brings the land reclamation and oasis productivity to its second maximum peak. In the 17-18th centuries the systems collapsed, structures were abandoned and irrigated agriculture decreased. The population declined and the region became dominated by nomadic herdsmen.

Phase 6. The modern irrigation system commenced in the period 1920-1936. A cross weir was constructed 25 km upstream of the town of Shaulder supplying concrete lined canals. Thus system was capable of carrying 8.9 m^3/s of water and was expanded to a potential capacity of 12-15 m^3/s in the 1970's. A series of deep drainage channels were added to the project starting in the 1950s to remove surplus water, control water table levels and salinity accumulation in the soil.

Impact of climatic variation on irrigation development

The former irrigation systems were developed over many centuries and it is probable that changes in climate will have produced periods of higher and lower agricultural productivity. At present there is little evidence available of these climatic changes in Central Asia.

Borienkov (2002) describes changes mainly in European Russia. Velichko (1995) compiled different studies from climate changes in Eastern Europe, where Gerasimenko (1995) described climate fluctuations in Southeastern Ukraine, considering the physical and chemical characteristics of the Holocene deposits, as well as the type of spore-pollen found, concluding that the last millennium was characterised by some more wet and cooler climate than today, in the subatlantic horizons. Klimanov (1995) explained the climate during the late glacial and the Holocene, including the Central Russian plain, as well as the paleoclimatic reconstructions about 1000 years B.P. where the mean temperatures at that time were 0.5°C above the present day values in the South of Ukraine and the rainfall in the Caspian region could be even less than today. A general global climate compilation was illustrated in a map by DeMeo (1998) where the north and south of the Caspian Sea was a wetter region between 6000 and 2000 BC, however there is no information about the region at the latitude of the Caspian Sea.

Aubekerovat et al (2003) describe a palaeoclimatic reconstruction at Tamgaly. Although this site is 1000km to the east of Otrar, it is at a similar latitude and covers the region where the main precipitation falls that supplies the Syr Darya. This was used to indicate the main climate patterns at Otrar in the period 500BC until today (Fig. 6).

The reconstruction points to conditions slightly cooler and wetter than present between 100BC-500AD and during the post-Mongol period (1400-1600). Relatively drier conditions similar to the modern day are indicated between 800-1200AD and after 1300. These two wet and dry phases correspond with the historical phases of expansion and contraction of human activities in the Otrar oasis.

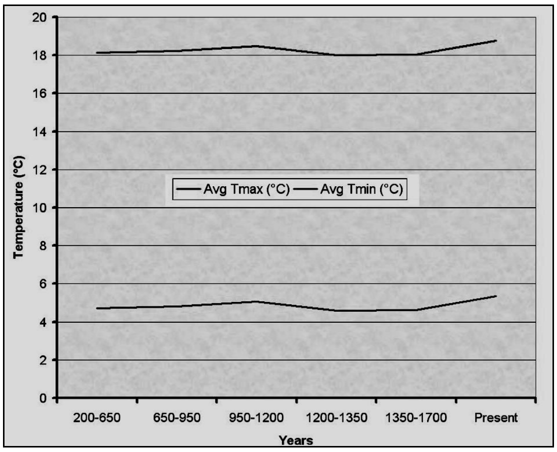

Figure 6a: Reconstructed average maximum and minimum annual temperature at Otrar. Source: Aubekerov et al (2003).

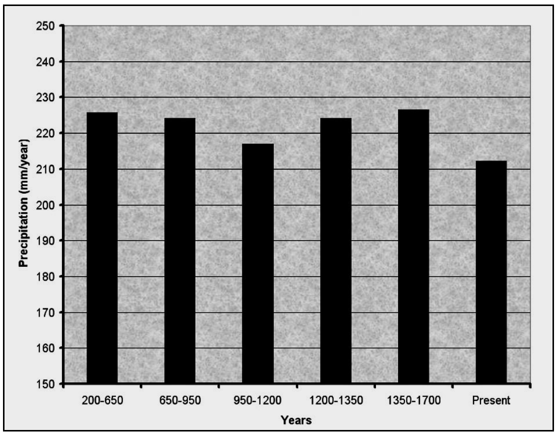

Figure 6b: Reconstructed average annual precipitation at Otrar. Source: Aubekerov et al (2003).

Reconstructing canal capacity and estimating irrigated areas

A series of survey visits were made between 2000-2004 to measure the dimensions of the main supply canals at key locations along the network. Each canal was measured for bed with, side slope, bed slope and berm width. These data were used to develop a typical trapezoid canal cross section.

The capacity of the surveyed channel cross sections was estimated using Manning's equation. Estimates of canal slope derived from

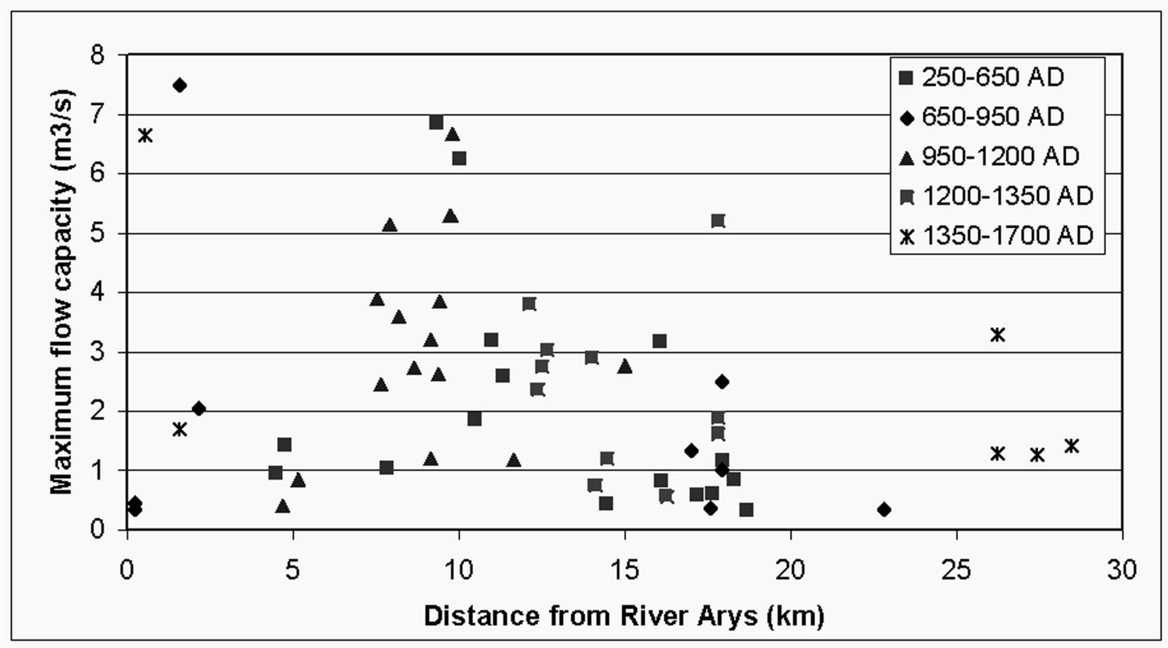

Figure 7: Canal capacity vs distance from river off take for 5 phases of development.

topographic maps and typical values for roughness coefficients were applied. These calculations provide useful data to calculate how much water could be delivered to each part of the former irrigation canal networks (Fig 7).

The area of crop that could be sustained by the calculated flows requires knowledge or assumptions of the crop type, root depth and the climatic conditions in each period of irrigation activity. The ongoing INTAS project is currently collecting grain types from various settlements in the project area and to identify which crops were grown in each period of irrigation activity. Primary crops identified include varieties of wheat and some rice.

Surveys of the main offtake channels where the canals meet the River Arys suggest canal capacities of 20-50 m^3/s, which is much greater than the modern average annual river flow of 15-25 m^3/s. This suggests that the main channels were either used as storage channels, or, more likely they were used as large offtakes to divert springtime flood flows for use in spate irrigation i.e. to divert a flood peak into the canal system whenever such floods occurred.

The area close to the river Arys (<10km) has been re-developed for irrigation several times and at present only the most recent canals are visible. At 15km from the Arys there is a significant knot of old canals (Fig 4). These have been surveyed and their ages determined and it is clear that the older canals had a smaller carrying capacity at this distance from the river. 6th Century canals disappear at 15km and 9th Century canals disappear at 20km, leaving only the 15th Century and modern canals at more than 30km. These preliminary results assist in identifying the extent of the system and more importantly the area of crop that could be grown at defined distances from the main river.

The modern irrigation system

To provide validation data for the above work, a parallel study of the modern irrigation system was carried out. The aim was to relate canal dimensions to crop types, climate, cropped areas and crop yield. Data were collected on the modern irrigation system which is superimposed on the ancient networks. Meetings with the managers of the local irrigation system allowed calculation of typical amounts of water used to irrigate the modern crops (cotton, maize, sunflowers and vegetable). Typical soil data for the region (grain size, water holding capacity) were available from Turkestan, a similar Oasis 100 km 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. The model is based on the United Nations FAO "CROPWAT" software (Clarke et al 1998). The model includes evapotranspiration calculations based on climate data (temperature, humidity, sunshine and wind speed) using the Penman Montieth equation, effective rainfall, simulation of soil moisture deficits and numbers of irrigations needed to maintain a healthy crop (Figure 8).

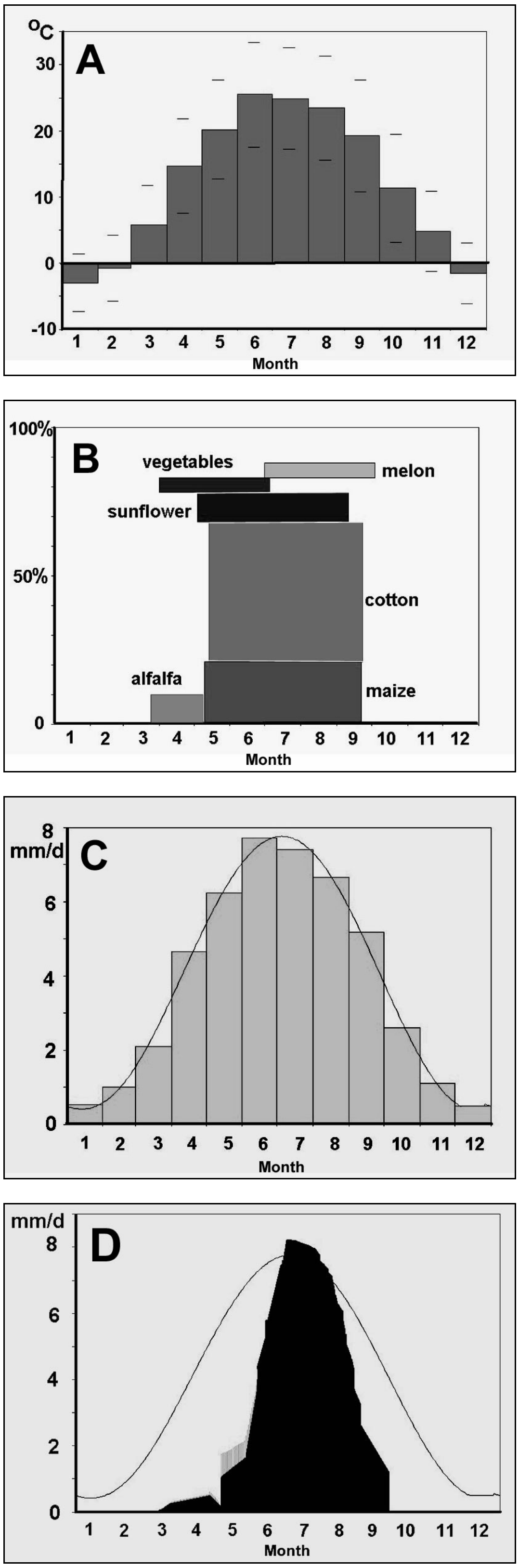

Figure 8: Simulation of modern irrigation system using Cropwat software,

A = average air temperature °C,
B = modern cropping pattern (maize, cotton, sunflowers & small vegetables),
C = Evapotranspiration from a standard grass surface in mm/day,
D = Crop water requirements, water needed in mm depth/day.

Table 1. Modern irrigation system water use (m^3)

Year / Water source (m^3)	2001			2003		
	From intake	To fields	*Efficiency*	From intake	To fields	*Efficiency*
Shaulder Canal	50,719,667	38,039,569	***75.0%***	67,560,744	50,670,560	***75.0%***
Kok Mardan Canal	4,239,626	2,789,764	***65.8%***	14,674,776	10,969,982	***74.7%***
Arys River (pumped)	6,474,990	6,474,990	-	7,188,438	7,188,438	-
Syr Darya (pumped)	34,014,723	34,014,723	-	49,184,817	49,184,817	-
Total	**95,449,006**	**81,319,046**	***70.4%***	**138,608,775**	**118,013,797**	***74.9%***

The simulation agrees well with the current system, notably that the capacity of the main canal limits the area of crops that can be planted and that crops grown furthest from the main canals often are short of water and have reduced productivity. The crop mixture requires water to be delivered into the soil at 0.88 liters/second for each hectare of crop at the peak of the growing season. This maximum figure is closely liked to the dimensions of the irrigation canals.

In the modern irrigation systems high water tables have created problems of salinity accumulation. Clarke (2001) estimated that capillary rise of 1-2mm/day occurs in areas where the a water table is less than 2m below ground level. This would contribute up to 25% of crop water requirements to crops such as cotton. No information on water table levels is available in the former irrigation systems, although some evidence of salinisation has been identified and is related to the gradual shift of the canal network onto higher areas to the north east of the river Syr Darya (See Figure 5).

Estimating system efficiency

Table 1 shows the canal distribution efficiencies in the modern irrigation system reported by Tugelbaev (2003). The efficiency of Kok Mardan Canal in 2001 was low (65.8%), improving in 2003, approaching 75%, similar to Shaulder Canal. In two years, the amount of water used in the fields was increased in 45% from 80 million m³ to 120 million m³ (approximate values). However, this data has to be taken with caution since there is no information about how the flow was measured.

Clarke (2001) made a detailed evaluation of surface irrigation practices for irrigated cotton at Star Ikan in the same district of Kazakhstan. In field efficiencies of water use by were approximately 60%.

Therefore, the overall efficiency is estimated as 75%*60%=45% and to deliver the required peak irrigation water requirement of 0.88 l/s to the crops 1.95l/s should be obtained from the source. This figure can be used to relate the dimensions of the canals to the areas that are irrigated

Actual water distribution measured in the year 2000 at Turkestan, 100km to the north was much less efficient (up to 70% losses), which may be more appropriate for simulating the former irrigation systems. For comparison, planned project expansion at Shaulder-Otrar in the 1970's aimed to increase the cropped area in the modern system to 10,000 hectares assuming an efficiency of 58%.

The modern main irrigation supply canal takes $10m^3/s$ from the river Arys. This flow would be possible to fully supply 5100 hectares of land at 1.95l/s/ha, assuming an overall efficiency of 45%. This is notably lower than the planned area of 8500ha. 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, gate structures being poorly calibrated and general dilapidation of the irrigation infrastructure in the last 10-15 years. During the site visits in 2003 it was clear that some 30% of the project area was not receiving adequate water from the modern system.

Another key observation is the presence of salts in the irrigated soils. The modern irrigation system has a series of drains to remove water from deeper in the soil profile to avoid the build up of salts and reduction in soil fertility. However these drains are not effective in all parts of the system.

Estimating the former population of the Otrar Oasis

Modern climatic data were adjusted to re-create the probable climate in the five stages of development of the Oasis of Otrar. The Cropwat software was used to simulate irrigation water requirements at the five phases. It was initially assumed that capillary rise did not contribute to crop water requirements and that irrigation applications and timings were correct. Interestingly, changes in temperature had a small impact on potential evapotranspiration, and although some periods were up to 15% wetter than at present, the irrigation schedules for all phases show significant lack of water in summer. If rainfall was 25% higher then there was just enough to grow one crop, showing how reliant agriculture was on irrigation. Therefore year to year rainfall variability was more likely to affect yields than higher temperatures or moister conditions.

The main canal feeding the city of Otrar has a capacity of up to 6 m^3/s. Assuming an irrigation efficiency of 30% and CWR of 0.88l/s/ha, this flow would probably supply at most 2045 ha of crops near a township. Preliminary results based on low to medium intensity patterns of crops suggest that crop yields were of the order of 0.5-1.5 tonne/ha under good growing conditions (i.e adequate water supply, no pest problems or crop diseases or soil salinity reducing yield). This indicates a possible crop yield of 1000-3000 tonne/y from the canal.

Messeth (2004) applied this methodology to the reconstructed climatic conditions for the five periods of development shown in Figure 5 and attempted to estimate likely population that could be supported by the agricultural outputs for the whole Oasis (i.e. all tobes). Shaulder Irrigation and Water Department (2004) states that in modern Shaulder, the annual crop yield for rice and cotton is in average 1.5 tonne/ha. However, considering that in ancient times the yield was lower than today, 1 ton/ha was assumed.

Using typical food value for cereal crops of 3500 calories/kg (Baden,1995), it was possible to estimate the population that might be supported by this crop based on assumed daily food requirements. Modern day estimates are that a person requires at least 1500 calories/day and to be fully effective 2200 calories/day (FAO,1996).

Table 2: Population estimates for the Oasis of Otrar in ancient times.

Period	1	2	3	4	5
Years (AD)	200-650	650-950	950-1200	1200-1350	1350-1700
Population	11770	11770	16730	21570	23000

Source: Messeth, 2004.

It is estimated that the population in the Otrar Oasis grew from about 10,000 in the first millennium to 23,000 people in the later periods (XIII and XVIII Centuries). This is in accordance to former population studies in Otrar Oasis, where in the last period 20,000 inhabitants were estimated by UNESCO (2004).

Field work on this project is ongoing and additional data on canal cross sections are being collected, together with analysis of grain types found in the excavations. We intend to relate the dimensions of supply canals with settlement size to determine the relative importance of agriculture at different stages of development of the Oasis of Otrar.

Acknowledgments

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