Water Hist (2010) 2:165–183
DOI 10.1007/s12685-010-0023-2

ORIGINAL PAPER

Structuring properties of irrigation systems: understanding relations between humans and hydraulics through modeling

Maurits Willem Ertsen

Received: 12 August 2010 / Accepted: 28 October 2010 / Published online: 23 November 2010

Abstract Irrigation systems were clearly important in ancient times in supplying crops with water. This requires physical distribution facilities and socio-political arrangements to coordinate between actors. Resulting systems are highly diverse, and are being studied extensively within archeology and history. Whether initiated by a central authority or emerging from small-scale initiatives, irrigation systems are shaped through activities of individuals, households, and small groups into patterns and landscapes. This article discusses how hydraulic modeling techniques are powerful methodologies to study such irrigation development. Modeling daily interactions by agents and water fluxes will build better understanding of irrigation systems as anthropogenic landscapes. Three case studies will be used to illustrate this argument. A current irrigation system in Arequipa, Peru, shows that one can relate irrigation infrastructure and social action. A second case from Peru on a pre-Colombian irrigation system suggests that one can link irrigation system, water flows, and settlement. In the third case in the Jordan Valley, this possible link between irrigation and settlement is further studied.

Keywords Irrigation · Modeling · Management · Spatiality · Power

Introduction

In order to produce a food surplus for their population, many civilizations in world history used irrigation. 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 urban kingdoms in many regions: Mesopotamia, Egypt, the Indus-valley, China, Mexico, and (coastal) Peru (Scarborough 2003). The well-known hydraulic hypothesis of Wittfogel (1957) links the development of civilizations to manipulation of water from larger streams for irrigating

M. W. Ertsen (✉)
Water Resources/Water Management Group, Department of Civil Engineering and Geosciences,
Delft University of Technology, PO Box 5048, 2600 GA Delft, The Netherlands
e-mail: m.w.ertsen@tudelft.nl
URL: http://www.wrm.tudelft.nl

areas without reliable rainfall (see also Scarborough and Isaac 1993). Although the viability of framing such direct links between water flows and social power may be discussed, it is clear that irrigation links water, humans, and infrastructure in producing an actual water transformation process. In canal irrigation, fields downstream along a canal are potentially at the mercy of the area upstream. If people upstream decide to close the tap, people downstream have serious problems. Although water distribution, canal management, and hydraulic properties are complex issues, and conclusions are not as straightforward as it seems in terms of upstream or downstream relations, it is also clear that canal irrigation is potentially hierarchical in nature (Ertsen and Van Nooijen 2009; Lansing et al. 2009).

Irrigation systems, spatial conglomerates of built elements, 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. Resulting systems are highly diverse. One only has to imagine the terraced rice fields in Asia, the large-scale irrigated plains of the western USA, or the small irrigated gardens in west-Africa to realize that the typical irrigation system does not exist. All irrigation systems are special, but they do share certain characteristics. Any irrigation system needs a source for its water. To divert water, an intake structure is needed. This can be an open canal, a weir, or a bucket. From the intake structure, a canal(s) bring(s) water to the irrigated area. Many irrigated areas have a certain hierarchy of canals, with larger (main) canals bringing water to diversion structures, with smaller (distribution) canals branching of from this structure to bring water to designated areas via smaller (lateral) canals. Drainage removes water from the irrigated area. Regularly, drainage water is used by irrigators downstream, directly or through the groundwater. User strategies have an impact on the system and the system constrains user actions. Hydraulic behavior of irrigation systems resulting from human action is partly constraining and partly enabling human action. Irrigation systems have structuring properties (Ertsen and Van Nooijen 2009; see Sewell 2005; Giddens 1984).

An important feature of irrigation systems is that they can even out water supply in a larger region and cancel out local fluctuations on system level, even though the systems are also subject to seasonality. "However, the relaxation of some local capacity constraints is attained at the cost of increased coordination and therefore increased coupling constraints within the larger system. The allocational conflicts, say between local flexibility in timing and overall watering efficiency tend to increase as do the regulatory and authority constraints associated with water management. In ancient irrigation as well as modern large-scale irrigation systems, water management is immensely important for watering efficiency and the level of agricultural output attained. It would have been a most rewarding task here to reinterpret the problems of regional irrigation system structure and management on the basis of a time–space constraints approach (capability/capacity, coupling, and regulatory/authority constraints)" (Carlstein 1982, p. 288).

The problems of irrigation referred to in the above quote are a subject of study within history and archeology, with many recent studies applying modeling and associated techniques (Adderly and Simpson 2006; Christiansen and Altaweel 2006; Herhahn and Hill 1998; Hunt et al. 2007; Lansing et al. 2009; see also Widgren 1979). The quantitative element is generally based on—seasonal—water balances, expressed in volumes needed for an entire season or year, although some sources include temporal fluctuations in hydrological patterns (Whitehead et al. 2008). Irrigation as agricultural practice is, however, about manipulating water flows in short time periods of hours and days—expresses in terms of liters per second—not about managing volumes representing time periods of months or even seasons. Results of the short-term manipulations may be expressed in water volumes on different and usually larger temporal and spatial scales, but it is not possible to work the other way around and derive potential manipulations of water flows on the required detailed level from such lumped volumes. As I have shown for a case in Peru, focusing on a water balance on seasonal level shows that certain management options were available. However, options to actually ensure that each day the required part of this volume would be available, which means diverting water flows each day from a river, may well have limited the actual options for management (Ertsen and Van der Spek 2009).

My article builds on the curiosity to discover how daily routines link to social and material structuration processes on smaller temporal and spatial scales, and how these routines transfer into longer term and large-scale continuities and transformations. I cannot stress enough that this is one of two fundamental differences with the majority of archeological studies so far—the other being my focus on water fluxes instead of water balances. How the irrigation systems underlying the ancient civilizations may have functioned, is not clear at all. As I will show, understanding hydrological and hydraulic aspects of ancient irrigation is already challenging, but including the human dimension is even more so. Irrigation systems develop as emerging anthropogenic landscapes from the purposeful, coordinated but often also uncoordinated activities of individuals, households, and small groups. An irrigation system may be initiated under central rule, by a strong state, but daily practices on the smaller scale would still determine success or failure of irrigation considerably. I argue that hydraulic and hydrological modeling techniques are powerful methodologies to study irrigation development, as these techniques allow careful study to discover how ancient irrigation systems have functioned in detail. It is the combination of modeling daily interactions by agents and water fluxes that will build better understanding of irrigation systems as anthropogenic landscapes resulting from activities of individuals, households, and groups, within hydraulic and hydrological boundaries setting the material context.

This article will outline this strategy using three case studies. The details available for analysis in each case study become less with each case. I start with an analysis of a current irrigation system in Arequipa, Peru. This case study does show that one can relate irrigation infrastructure and social action. After some remarks on theoretical and methodological implications from this first case, a second case from Peru is introduced. This case deals with the pre-Colombian irrigation system on the Pampa de Chaparrí. The results from this case suggest that one can link irrigation system, water flows, and settlement in the area. In a third case, from the Zerqa triangle in the Jordan Valley, this possible link between irrigation and settlement is further studied. I will end this article with some general conclusions and an outlook for further research. However, first we move to Arequipa, Peru.

Arequipa, Peru

The city of Arequipa is the capital of the province with the same name in south Peru. The city has an average elevation of approximately 2380 m above sea level. Furthermore, Arequipa has approximately 900,000 inhabitants, making it the second largest city of Peru. The irrigation system in Arequipa is managed by three organizations: the Administración Técnica del Distrito Riego (ATDR), the Junta de Usuarios, and several Comisiónes de Regantas. The irrigation system in Arequipa is under the jurisdiction of the Chile department of the ATDR department, a governmental organization. The ATDR regulates the daily discharge in the river Chili in consultation with other stakeholders, and is concerned with conflict management within the irrigation system. The area supervised by the

Table 1 Overview of characteristics of the three irrigated areas

	Age (years)	Irrigated area (hectare)	Number of plots	Average plot size (hectare)	Average farm size (hectare) 2001	Average farm size (hectare) 2007	Water availability (l/s)	Water availability (l/s per hectare)
Alta Cayma	>500	441	931	0.47	0.57	0.54	550	1.25
Zamácola	80	1364	794	1.72	2.221	2.17	1650	1.20
Alta Cural	20	870	374	2.33	2.5	2.32	520	0.60
Total		2675	209.9	1.27	–	–	2720	0.98

ATDR is divided in two districts each managed by a Junta de Usuarios (Chili zona Regulado and Chili zona no Regulado). The district Chili zona Regulado is divided in fifteen Comisión de Regantas. Finally, the level of Comité de Canal, seen in the north coast of Peru (Vos 2002), is absent in Arequipa.

The Junta de Usuarios is a federation of all Comisiones de Regantas in an irrigation district. The main tasks of the Junta de Usuarios are operation and maintenance of the primary canal and conflict management at primary and secondary level. In addition, the Junta is concerned with the planning of the water allocation for next year. A Plan de Cultivo y Riego is set up to give a detailed guideline for efficiently allocating water. In the Plan, the water demand per plot is calculated. However, some farmers do not fully participate in announcing which crops they are cultivating, and discharge records are hardly available. As a result, the Plan is not too accurate and therefore not applicable at the level of the Comisión de Regantas. A Comisión consists of farmers from the region and external employees. The main tasks of a Comisión are water allocation and maintenance of canals at secondary and tertiary level. Furthermore, the Comisión is concerned with conflict management within the tertiary block. Comisiones de Regantas have two water guards to check all water structures within the area. Technical problems are directly transferred to the Junta de Usuarios.

To find out how irrigation actually works in this area, three Comisiones de Regantas will be discussed in more detail, Acequia Alta Cayma, Zamácola, and Alto Cural. An intensive fieldwork campaign was conducted in the period between September 2007 and March 2008, including interviews, canal measurements, and participatory observations. This fieldwork was supported by hydraulic modeling.[1] The three Comisiones cover approximately 2600 ha which represents 35% of the total irrigated areas in the district Chili zona Regulado. With approximately 2100 water users, the average plot size in the area is 1.24 ha. As Table 1 shows, however, differences between Comisiones are considerable. The irrigation water from the river Chili is supplied to the Comisiones by one main canal. This Canal Madre Zamácola starts at the river Chili, runs along Acequia Alta Cayma, through Zamácola, and ends up at the head of Alto Cural (Fig. 1). The average discharge at the inlet of Canal Madre Zamácola is approximately 4.2 m^3/s. Between Acequia Alta Cayma and Zamácola an offtake is located which retrieves 1.5 m^3/s for the

[1] The fieldwork was done by Eljakim Koopman in the context of his traineeship with CAMP SRL, and his MSc graduation project (Koopman 2009).

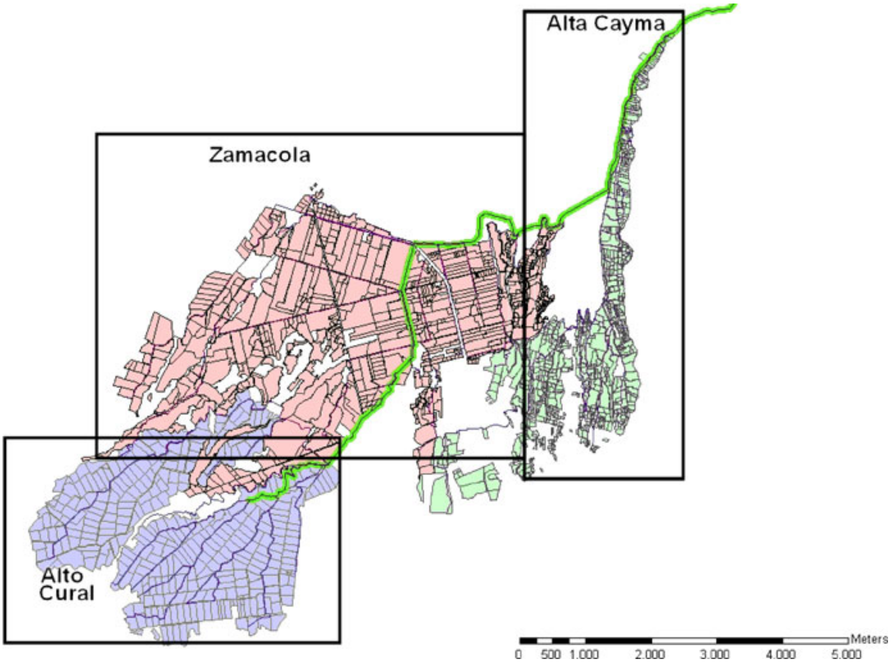

Fig. 1 The three Comisiones de Regantes

preparation of domestic water. This leaves approximately 2.7 m^3/s for irrigation, which is about 1 l/s per hectare.

However, Acequia Alta Cayma and Zamácola receive two times more water per hectare than downstream Alto Cural (Table 1), although discharges are supposed to be proportional to the demand area. The water availability of Acequia Alta Cayma is relatively stable, as it is not influenced by actions of fellow water users. Furthermore, discharges through its two orifices used as intakes are less influenced by changing conditions upstream compared to Zamácola and Alto Cural. Finally, Acequia Alta Cayma users can change the discharges in their secondary canals. Thus, when conditions change, water users can manipulate the orifices to their benefit. In Zamácola, proportional water division structures divide the discharge upstream of the structure proportionally to the secondary canals, thus dividing the relative increase/decrease in the primary canal to the secondary canals. Orifices bring water from secondary canals to field canals, through intermitted flow, meaning they are opened/closed according to a rotation scheme. Although Zamácola's water availability is influenced by the actions of water users in Acequia Alta Cayma, even when Acequia Alta Cayma consumes as much water as possible regarding its canal capacities, enough water remains for Zamácola to irrigate. The downstream area Alto Cural totally depends on the actions of Acequia Alta Cayma and Zamácola. Due to the low hydraulic flexibility of the sub-irrigation system, the water availability of Alto Cural is quite uncertain.

In terms of profitability of agriculture, benefits are not equally spread either. Although Acequia Alta Cayma has the benefit of ample water supply, its small plot sizes make profitable agricultural practices less possible. The small plot sizes are probably caused by a long history of inheritance. From the scarce data available, one can observe declining farm sizes in all three area between 2001 and 2007. As Alta Cayma is by far the oldest system, probably predating the Spanish conquest, this fragmentation process would have been long. Due to a low profitability from their small plots, most farmers in Alta Cayma perform other activities, and do not give top priority to their agricultural practices. Their level of involvement in participating in irrigation management is very low as well. Tax recovery of Acequia Alta Cayma is a little over 60%, which may indicate unwillingness of many farmers to pay the water tax. Furthermore, land use in Acequia Alta Cayma is changing rapidly. Plots are sold for urbanization purposes. Nevertheless, water needs in Acequia Alta Cayma can be dealt relatively easy. There is room to allocate more water to the farmers than prescribed in the Plan de Cultivo y Riego.

In Zamácola, farmers are generally satisfied with the water availability and the way it is allocated, although sometimes they encounter water shortage, especially from August to October. Up to 90% of the farmers pay the water tax. The facilities of the Comisión de Regantas for the water guards were more extensive in relation to the other Comisión de Regantas. For example, the water guards had motorcycles and offices. In Zamácola the Plan de Cultivo y Riego is taken very seriously. It is used to check the water use of farmers and farmers use it to decide the crop they want to cultivate. The Comisión de Regantas Zamácola has assisted the farmers via facilities for storage, for example, cooling cells, and establishing a good relation with the buyers of the agricultural products. Finally, most products of Zamácola have a quality label, on which the farmers and the president are very proud. Quite a few farmers in Zamácola have constructed their own farm reservoirs to deal with unpredictable water availability. Apparently, there is enough water available on average to construct these devices. Since the reservoirs are paid for by the farmers, it indicates that farmers have enough resource to install them.

The main problem in the downstream area Alto Cural is the lack of irrigation water. The current configuration of the irrigation infrastructure, both in terms of hydraulic behavior of the canals as in terms of the downstream position, results in water supply being inadequate to meet the water needs of Alto Cural. This could illustrate a weak position of negotiation of Alto Cural regarding the other stakeholders in the irrigation system. Farmers complain a lot about water shortage and even accuse Zamácola of repeatedly stealing water. Much distrust is present among the farmers in the area itself as well, and regarding the Comisión de Regantas and Junta de Usuarios. One might expect from superficial observations that Alto Cural would be highly organized since Alto Cural has on average the largest plots, the most structured canal layout, and the newest irrigation system. In Alto Cural, the lack of irrigation water may translate in farmers not willing to organize, as there is nothing to organize for, even though they have on average the largest plots and youngest irrigation system.

The three Comisiones de Regantas operate in the same legal context and share the same main canal. Nevertheless, the way the Comisiones and their water users are organized varies considerably. In Acequia Alta Cayma, profitability is low and farmers appear to be unwilling to participate in irrigation organization. Acequia Alta Cayma has a surplus of irrigation water at all times anyway, which may not give an incentive for collective organization (Uphoff et al. 1990). For farmers in Alto Cural, low agricultural profitability is due to the lack of irrigation water. As argued by Levine (1980) and Keller (1986), such water scarcity may lead to unwillingness to participate. In Zamácola, profitability is relatively high, and farmers participate in projects initiated by the Comisión de Regantas. In turn the Comisión de Regantas assists/supports farmers, which probably increases participation. Water availability of Zamácola is sufficient on average, which means that the available volume for a season is ensured, but when water is actually delivered through the canal is unpredictable in time. The total volume is more or less secure, but the actual daily flows are less predictable, which may lead to a niche for an effect organization regarding water distribution (Uphoff et al. 1990). As a response, farmers have invested in farm reservoirs, which store the volume and make farmers less dependent on short-term flows.

Integrating the three H-domains

The Arequipa case shows that canals and other objects set the material and spatial reality, within which social interaction shapes spatial patterns of water flows and related actions through time. At the same time, social interactions intervene in the material and spatial reality. Such social production of space "is not a smooth and automatic process in which social structure is stamped out, without resistance or constraint, onto the landscape. […] Spatiality must be socially reproduced, and this reproduction process presents a continuing source of struggle, conflict and contradiction" (Soja 1985, p. 97). Reproduced over time, the resulting pattern may appear as something stable and persistent, but spatiality can also be "substantially restructured, invoking again its origins and grounding in social practices and the labor process" (Soja 1985, p. 94). The production of space is both the medium and the outcome of social actions and relationships (Soja 1985, p. 94); hydraulic infrastructure in irrigation systems can be conceptualized as structures in the way Giddens defines them: structures are medium and outcome of social practices through everyday actions, in which routines are an important phenomenon (see Giddens 1984; Sewell 2005).

These interactions, routines, and structures in irrigation are shaped within a context consisting of the domains of Hydrology, Hydraulics, and Humans (Fig. 2). These three H-domains interact: the natural environment sets boundary conditions for humans, to which humans respond with irrigation technology, with such responses impacting both boundary conditions and humans anew. Such dynamic irrigation systems, or irrigated landscapes, are complex adaptive systems, as "[…] at present these concepts represent one of the most promising tools for analyzing complex and messy landscapes through long chronological spans of time" (Wilkinson 2003, p. 14). Notwithstanding the valuable insights available studies already yield on human–environment interactions in ancient societies, there is a clear need to develop new approaches to improve our understanding of ancient irrigation. For example, current complex adaptive systems and agent-based modeling focus on rain fed agriculture (Altaweel 2007; Wilkinson et al. 2007a, b). In a volume edited by Kohler and Van der Leeuw (2007), the single paper on irrigation (Janssen and Anderies 2007) is fascinating with its highly stylized formatting of irrigation. However, it also illustrates that the current state of the art in the field is based on lumped water balances, which do not take into account short-term variability in water fluxes.

Irrigation systems are the material form of social structures and relations, where comparable physical layouts of irrigation systems can result in quite different irrigation management and social relations (Hunt 1988). The arrangements for the different physical elements/properties of irrigation systems represent many issues in need of solving by irrigators on daily basis. Obviously, physical realities do not determine the actual trajectory of development, but they do exert a considerable influence on landscape development at every stage, basically offering ranges of possibilities (Wilkinson 2003, p. 11). Studying landscape or irrigation system changes over a long time-span obviously has its restrictions, as one cannot include each and every detail. The so called signature landscapes, a coherent group of component features, including tracks, fields, canals, religious features that relate to a single entity or time period (Wilkinson 2003, p. 11), need to represent specific

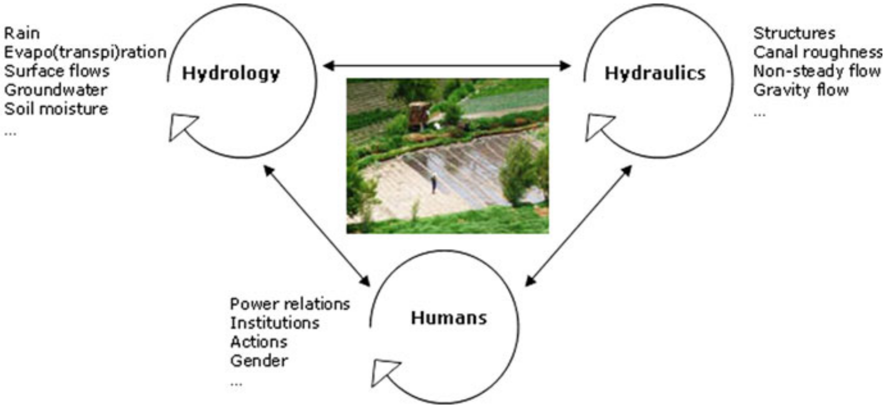

Fig. 2 The three H-domains

moments in the evolutionary history. Understanding irrigation system development as anthropogenic landscapes emerging from the purposeful but uncoordinated activities of humans needs to include the stochastic nature of water availability on different time scales, varying from fluxes in periods of minutes and hours to balances in periods of years and decades. The modeling approach to study and generate these fluxes and balances in ancient environments needs to be developed. Below I will give some first results.

Pampa de Chapparí, Peru

Despite its arid environment, ancient civilizations have prospered on the Peruvian coast. The narrow coastal plain is a desert with river valleys separated by areas with little or no vegetation. The rivers flowing from the Andean mountains to the west provide the fertile coastal valleys with irrigation water. The valleys are oases, and exploitation of their agricultural potential depends on irrigation, although some small, highly productive areas do not require irrigation (Kosok 1965; Netherly 1984). Ancient Peruvian irrigation systems have been studied extensively from different perspectives, including management, state formation, hydraulics, and water use (e.g., Eling 1987; Farrington 1980; Hayashida 2006; Kosok 1965; Netherly 1984; Nordt et al. 2004; Téllez and Hayashida 2004). The intense debate on hydraulic calculations for pre-Colombian canals shows the need for good data, but also for well-based hydraulic assumptions, calculations, and modeling. Most hydraulic calculations available have been based on assumed uniform flow conditions. Due to canal dimensions and variable flow patterns, however, uniform flow may have been the exception in the canal systems under study. For individual canals, especially the longer ones, for example, for the Chimu Chicama-Moche Intervalley canal (Ortloff 2009; Ortloff et al. 1985), uniform conditions for some or even most of their length can be assumed. For shorter canals, particularly in networked systems with structures, assuming uniform flows would not be correct. The mathematical formulas describing non-uniform conditions cannot be solved analytically and require numerical hydraulic modeling techniques.

On the Peruvian north coast, the Andean rivers provided the fertile coastal plains with irrigation water. Irrigation canals diverted (part of) the water available in the rivers. Some canals had two intakes, with one being used when the water level in the river was low

(Netherly 1984). The river water level was probably raised to divert water into the canal by means of stone and brush weirs (Netherly 1984; Eling 1987). These weirs were built in the river to guide part of the river flow into the canal. Such diversion systems are still being applied in Peru and many other regions worldwide. They are relatively cheap in terms of money and (usually) labor, although they need regular replacement as they will be washed away during floods. Peruvian conveyance canals could be rather long and often required aqueducts to pass small side valleys. Sometimes canals were cut into rock to maintain the grade. Canals were frequently stone-lined; others became lined with the clay sediments in the irrigation water settling in the canal (Farrington 1980; Kosok 1965; Netherly 1984).

The Pampa de Chaparrí, located on the north coast of Peru close to the city of Chiclayo, received its water from the Río Chancay, which becomes the Río Reque in its downstream segment. The irrigation system of the Pampa de Chaparrí was used between 900 and 1532 AD by the Sicán, Chimú and Inca civilizations (Nordt et al. 2004). In the 16th century, the system was abandoned. Apart from the Pampa de Chaparrí, two other areas downstream were irrigated from the Río Chancay. Furthermore, water from the Río Chancay was diverted to the Río La Leche through the Pampa de Chaparrí main canal and the Río Sanjon. It is not unlikely that this diversion to the Río La Leche only carried water, when water availability in the Río Chancay was high and excess water was not used in the Pampa de Chaparrí. Téllez and Hayashida (2004) discuss how canals and walled fields on the Pampa may have been constructed with organized labor replacing taxes. Nordt et al. (2004) discuss soil fertility and show that infiltration capacities of the coastal soils and low salinity levels in the irrigation water would have given no problems related to salinization. Furthermore, they studied crop water requirements, irrigation patterns, and soil moisture.

Water on the Pampa was distributed through the Racarumi canal system. The Racarumi I canal is the main canal conveying water from the river through an intake about 10 km to the east of Chongoyape. No fields have been found along this canal before it reaches the Pampa. From canal I three distribution canals (Racarumi IIa, IIb, and IIc) divert water. On the Pampa as a whole some 5600 ha of ancient cultivated fields were detected. About 3300 ha were watered by the Racarumi II canal system (Hayashida 2006). Inflows into the canal system of the Pampa de Chaparrí were highly dependant on water levels in the Río Chancay. Given the strong fluctuations within months, water levels in the canal may have fluctuated considerably within shorter timeframes. This difference in water level can considerable, and would have strong implications for flow distribution within the system. It is even possible that much more water would have been diverted than what was needed. This is not that likely, however, as there is no evidence that flood waters ever inundated the adjacent agricultural fields (Nordt et al. 2004). Elsewhere I discussed how crop water requirements and irrigation strategies on the Pampa may have been (Ertsen and Van der Spek 2009). To distribute these requirements and enable the strategies, the water had to be channeled to the fields. How ancient Peruvian irrigation systems like the Pampa de Chaparrí were managed is unclear, but permanent gates or diversions have not been found in ancient irrigation canals on the north coast. Distribution structures were probably temporary and constructed of earth, stones, sticks, and brush (Eling 1987; Hayashida 2006; Nordt et al. 2004). After building a temporary barrier, cutting a breach in the canal bank upstream of the barrier would be sufficient to irrigate fields. Permanent distribution sluices were introduced by the Spanish colonizers (Netherly 1984).

To analyze the irrigation system on the Pampa, a schematization of the main system was made in the hydraulic model SOBEK. The system was defined as consisting of the main canal Racarumi I, with three secondary canals branching off (Racarumi IIa, IIb, and IIc) (Fig. 3). Dimensions of these canals were based on combining two assumptions. First, it was assumed that canal dimensions on the Pampa would be comparable to canal dimensions as reported by Eling (1987) for the Jequepeteque Valley close by. Second, it was assumed that canal dimensions would be proportional to irrigated area of the canal. These two assumptions gave canals bed widths ranging between 1.4 and 1.8 m. The larger, upstream Racarumi I main canal has an assumed bed width of 3 m. Maximum water levels were set at 1.5 m, again with Racarumi I main canal being the exception with a maximum water level of 2 m. The bed gradient for all canals was set at 0.0018, the side slope gradient at 1, and the Strickler roughness factor at 30 $m^{1/3}/s$. This canal system served as the reference layout, with canals assumed to be connected without special structures to regulate flow. Next to this reference layout, two extra layouts were created in the model. In the layout "Main System," the canal system is equipped with low weirs in the main canal Racarumi I just downstream of the off-takes to the secondary canals. These weirs are 4-m wide with a crest height of 0.5 m. In the third layout "Proportional System," the canal system includes weirs in both ongoing and off taking canals. These weirs are 4-m wide and have crest levels of 1 m. With the weirs being the same, the incoming flow will be split equally between the two canals downstream.

These three layouts represent different possible irrigation system realities on the Pampa, with different material properties and options to manipulate flows (Fig. 4). Flow patterns in the three layouts were studied with two different incoming discharges at the head of the system. First, a gradual increasing and decreasing incoming discharge was modeled. This gradual pattern was used to study when the different layouts for the canal system were "full", defined as the state when at one location in the system the water level reached its maximum value. For each scenario, the associated discharge was taken as the maximum discharge capacity of the respective system layout. In a second step, the incoming discharge was defined less gradual, and included two sudden changes in discharge, resulting in fluctuations throughout the canal system. Combining the three layouts and fluctuating incoming discharges resulted in an additional three scenarios. The fluctuating pattern was

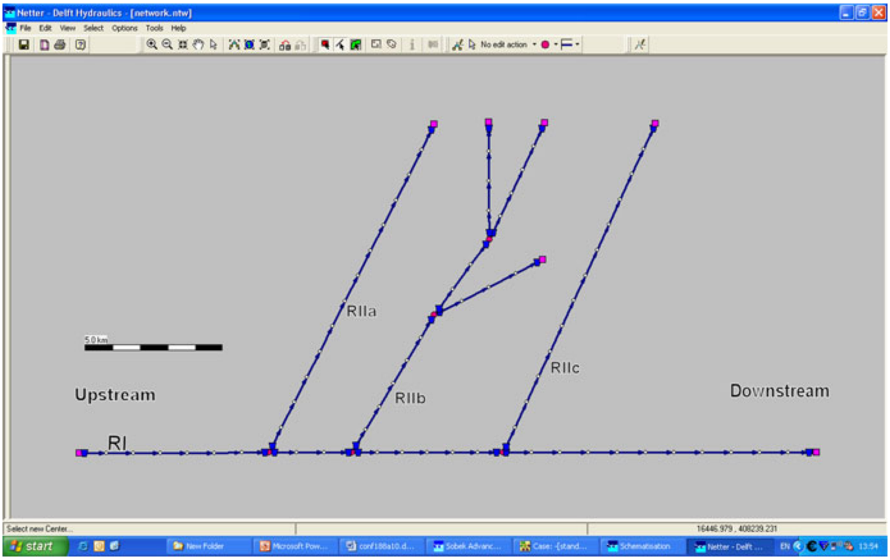

Fig. 3 The canal system of the Pampa de Chaparrí in the model

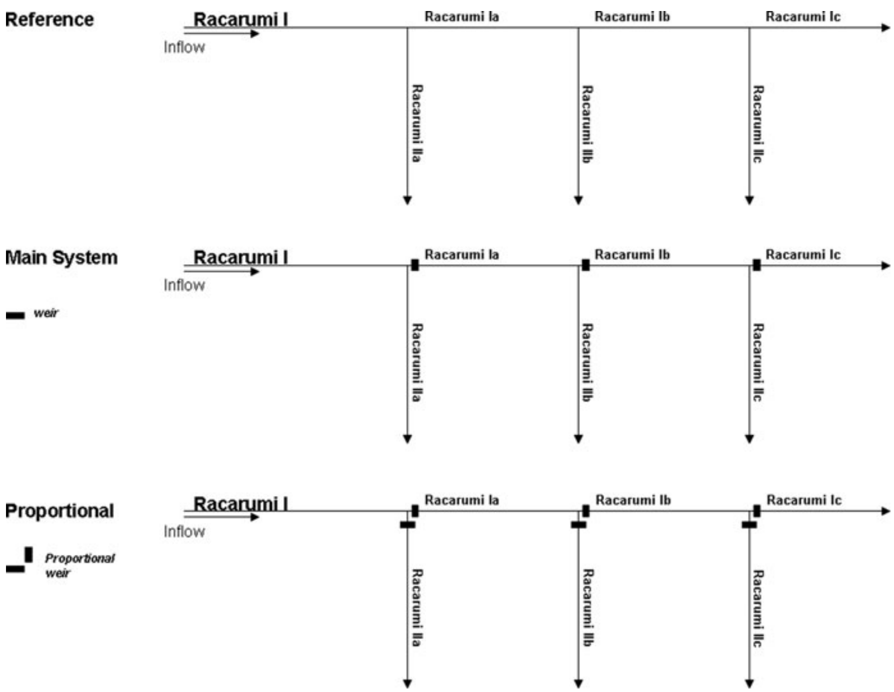

Fig. 4 Schematic view of the three different layouts

used to study relative implications of changing incoming water flows on water availability in the secondary canals.

The distribution of the incoming discharge through Racarumi I main canal over the secondary canals IIa, IIb, and IIc, and what is left in RIc for the three layouts is presented in Table 2. The table gives the flow distribution within the gradual flow pattern at the moment that the system reaches maximum water level somewhere in the system. In all three cases, the point reaching maximum water level was the location where Racarumi IIa branched of from Racarumi I. Generally speaking, it is obvious that in a canal system with few control options, less water is available downstream compared to upstream. The distribution of the discharges over the canals is fairly similar between layouts in terms of percentages for each secondary canal. The potential inflow is much lower for the proportional system, however. This is probably mainly caused by the heights of the weir crests, which yield higher water levels within the system.

With fluctuating incoming discharges at the head of the canal system, the secondary canals will show a certain fluctuation as well. One can imagine that farming under changing conditions is more difficult than when conditions are stable. An interesting question with fluctuations in discharges is whether changes in inflow are distributed equally over the entire system or not. In other words, would all the farmers in the irrigation system experience similar fluctuations? It could very well be that downstream canals show more flow fluctuations compared to upstream canals, or the other way around. Furthermore, it could be that canals show similar fluctuations in order of magnitude, but different in timing. The three layouts were modeled with the fluctuating incoming discharge. Figure 5 shows that the reference canal layout distributes the fluctuating inflow in RI into the

Table 2 Discharge distribution for the three scenarios at full supply

	Reference and main system		Proportional	
	m^3/s	%	m^3/s	%
RI	7.2	100	4.3	100
RIIa	3.2	44	2.1	49
RIIb	1.9	26	1.1	26
RIIc	0.8	11	0.5	12
RIc	1.3	18	0.6	14

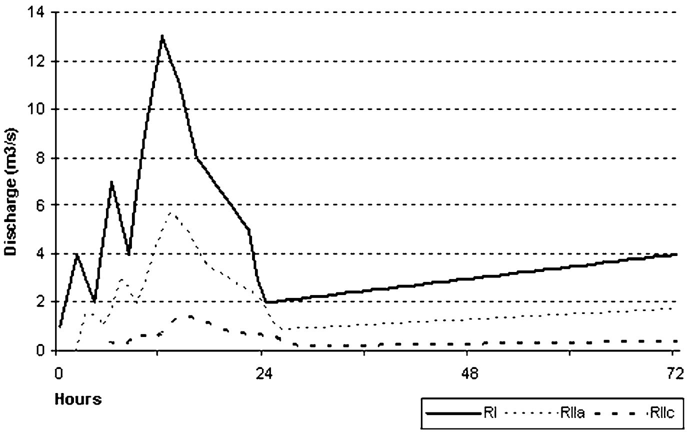

Fig. 5 Discharge fluctuations for the reference layout

upstream secondary canal RIIa and the downstream RIIc. Although there is a time gap between the input fluctuation and the response of the two canals, with RIIc lagging behind a little, the shape of the response is similar for all canals. In other words, fluctuations in inflow are more or less equally spread over the entire system.

On the other hand, Fig. 6 shows that the responses of the upstream and downstream canals for the two other layouts are less equal. The figure shows the relative discharges of the canals RIIa and RIIc, defined as the proportion of inflow in relation to the flows in Fig. 5. For example, if the inflow in RIIa at hour 24 in Fig. 5 is 2 m^3/s and in one of the scenarios of Fig. 6 would be 3 m^3/s, the relative discharge would be 3/2 equals 1.5. A first look at Fig. 6 shows that all relative discharges are above 1, which means that in both scenarios with control structures—main and proportional—actual inflows in the secondary canals are higher than the reference inflow.[2] Figure 6 also shows that the proportional layout shows less fluctuations compared to the layout with weirs only in main canal RI (Main System). Furthermore, in the Main System layout fluctuation seems to be much stronger in the downstream canal RIIc than in the upstream canal RIIa. Although this larger fluctuation is partly caused by the low discharges in RIIc in the time frame under study—a difference between 0.3 and 0.2 m^3/s in such circumstances is relatively significant—a

[2] This seems to be in contrast with Table 1, but that table shows the discharge distribution at full supply, whereas in the timeframes studied for fluctuations full supply is not reached yet.

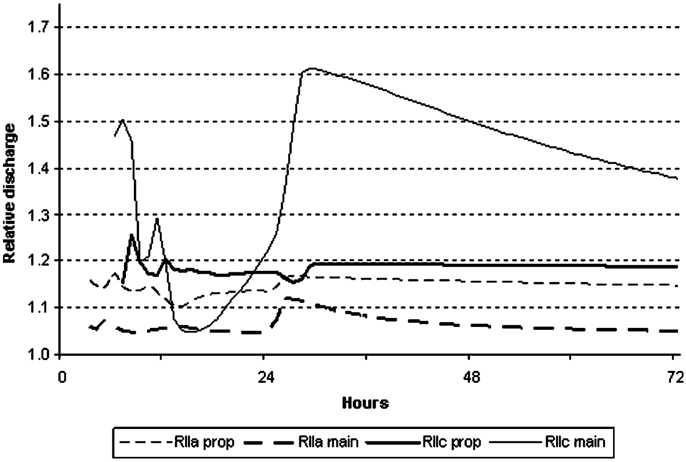

Fig. 6 Discharge fluctuations in two time frames for two layouts relative to reference

farmer irrigating in the time frame with the relatively higher discharge would still have a clear advantage to farmers irrigating earlier or later.

For the Pampa, Netherly (1984) suggests that control structures were unnecessary because of the segmentary rights and obligations associated with canals. Different social groups had their own canal to manage, with conflicts between these groups being resolved by a central ruler. Although such a system of apparent isolated management of canals within one larger canal system seems perfectly possible, the absence or presence of control structures would still have its hydraulic effects, as is shown above. Hydraulically speaking a non-existent structure or an open canal is still a structure, with its associated responses to changing water levels, discharges, and human actions. As water storage at system level seems to be absent, buffering water demand and water availability would have been impossible. The modeling discussed above is far from complete. There is still much to work on, especially in combining this type of hydraulic modeling with analysis as made by Ertsen and Van der Spek (2009). Simple as it may be, the modeling does suggest uneven water distribution in terms of volumes and reliability over the Chaparrí system, with more predictable and ample flow in the upstream part.

How does these results from a hydraulic model relate to the material evidence found on the Pampa? Obviously, ultimately water availability in a canal system is the result of hydraulic properties and human actions together. Even though gravity irrigation systems do enforce upstream–downstream dependencies, the actual outcome—whether the upstream or the downstream "wins"—is the result of social struggle and/or negotiations. There is some evidence available through aerial photographs of the Pampa de Chaparrí, indicating three areas with properties that can be attributed to their respective position within the irrigation system. The canal and field patterns in these three areas can be linked to the water reliability pattern found in the modeling. Each area is characterized by differences in layout of fields and canals and is associated with different management practices (Hayashida 2006).

Upstream in the canal system, as it would have received its water from the upper sections of canals RIIa and RIIb, a 900 ha area shows a highly regular canal system. It could be either a single, large plot or a series of identical plots in strips. As discussed by Netherly (1984), such upstream fields may have received most water and thus been able to produce two crops a year. In the hydraulic model, fields in this area received most water as well. With water available, it would have been possible to invest in canal infrastructure. In the upstream area, centralized management, perhaps state production, may have been the case.

In contrast, an area most downstream on the Pampa, as it would have received water from canal RIIc, has an appearance of a patchwork of varied plots and some minor canals (Hayashida 2006). The fields suggest that agriculture was practiced in this area, which would have been very unlikely if crops only depended on rain—which is basically zero. As the layout of fields and canals at least suggests that canal water was less important, it is not that strange to suggest that groundwater may have been used a source in this area, in line with the different types of irrigated fields given by Netherly (1984). These lower areas may have been managed by farmers for their own support. In the area between these clear upstream and downstream areas, along the lower RIIa en RIIb canals, layouts of canals and fields are variable in shape, but still fairly regular. In line with what I suggested above and in the Arequipa case, this may indicate a reasonably predictable water supply. This reinforces the need to never accept possible hydraulic-induced water distributions immediately.

Zerqa Triangle, Jordan

For my final case, irrigation in the Zerqa Triangle in Jordan is studied.[3] As much as elsewhere in the Ancient Near East, human survival in the Zerqa triangle in the Jordan Valley depended on human ability to adapt to the natural environment, not just in the reactive sense, but also in the proactive sense of shaping the environment. The Zerqa triangle has been extensively studied within the Settling the Steppe-project (Kaptijn 2009; Van der Kooij 2007). Average winter temperature in the area is 15°C, while the summer average is 32°C and maximum daily temperatures of 40–45°C are quite common. Rain falls between November and April, with an average of about 290 mm a year and a large inter-annual variability. Theoretically, the average may be enough to sustain dry-farming, but frequent droughts would make it impossible to feed a society of some size without a more secured water supply from irrigation. Before the 1960s, a canal system with three main channels tapped water from the Zerqa. In 1920, inhabitants of the Zerqa Triangle stated that neither they nor their direct predecessors constructed the channels: they only cleaned existing ones (Kaptijn, this issue; Kaptijn 2009). The likely farming society from which these people inherited their irrigation system was the Mamluk period (1260–1500 AD), when the Valley was widely used for sugar cane cultivation.

As discussed in this article, both material aspects of irrigation—for example, crop water requirements—and interactions between material and social—for example, water distribution—are important. Kaptijn (2009) showed that—on average—the base flow of the Zerqa River would have been sufficient to irrigate the area potentially served by irrigation canals tapping from the river. In the area, however, rainfall and soil moisture are important aspects of the water balance; in semi-arid areas, the average is not very informative about agricultural possibilities, as no year tend to be average (see Ertsen and Van der Spek 2009). Furthermore, in many canal irrigation situations comparable with the Zerqa triangle, irrigation from a river as the Zerqa is not the single source of water, but is used to

[3] Much more detail can be found in the article of Eva Kaptijn in this same issue. I am extremely thankful to Eva Kaptijn for the discussions leading to this article and allowing me to use her basic material. 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 developed during the workshop on Water and Power, University of Durham, UK, organized by Tony Wilkinson, from which this volume originates.

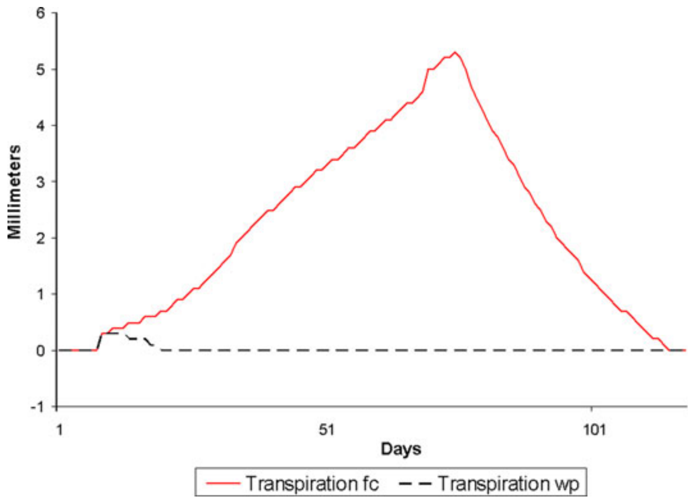

Fig. 7 Two cereal crops with different starting conditions

supplement the rainfall which will be available most of the years in the growing season. The actual start of the growing season is largely determined by rainfall. 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 into the dry season. The difference between a good and a bad choice may be defined as having a harvest or not.

Evapotranspiration—which means growth—of a wheat crop planted in November with rainfall averaged over the growing period is shown in Fig. 7. One of the crops is forced to start in dry soil at wilting point (wp), when crops cannot extract the water in the soil anymore.[4] The other crop is allowed to start with the soil being at field capacity (fc), meaning that the soil contains the maximum amount of water for crops to be extracted. This crop manages to develop, producing a biomass of 8.3 ton per hectare, with an actual yield of wheat of 2.5 tons per hectare. Our poor dry crop did produce some biomass, but the 0.135 tons per hectare never managed to produce a yield. Calculations confirmed that a single "rescue" irrigation gift relatively late in the season, 100 days after sowing, with dry starting conditions would be too late, as the crop already died. The graph also suggests that full irrigation during the entire season would not be 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 vital during the growing cycle, with less water required per gift. This not only shows the importance of starting conditions in terms of actual moisture in the soil when studying irrigation and yields, but also suggests that rain fed agriculture is an option on the Zerqa plain when soils can be brought to fc early in the growing season. This could be achieved with a pre-sowing irrigation gift.

[4] Calculations were made in Aquacrop, a crop water model developed by the Food and Agricultural Organization. http://www.fao.org/nr/water/aquacrop.html.

Another issue is how the water required to sustain crops could be delivered to the fields in the Zerqa area. It is likely that arrangements developed within canal systems in the Zerqa area, with communities probably cooperating in some way. We have some information available on the pre-modern clan-based society in the Zerqa triangle. There was a distinction between the different clans (Fig. 8), with the powerful Hurr clans—Mamduh and Shararah—who regarded themselves as free and stemming from the Bedouin, and the second rate Ghawarneh clans were regarded as foreign (Kaptijn, this issue). A canal model was developed in SOBEK, the same software as the Pampa case. Each main canal was simplified by equipping the canal with off-takes irrigating sub-areas of 50 ha. Canal cross sections and slopes were based on data available on the situation before 1950 AD. Different scenarios were tested, including starting irrigation upstream or downstream and canal infiltration. For each scenario, it was calculated how much water would enter each sub-area during a 30-day interval. The total volume delivered to each sub-area was compared to a reference volume. As it is unknown what management was applied in the Zerqa triangle, the relative certainty of water delivery to each sub-area from a hydraulic perspective, 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—with contours of 20% (Fig. 8). The location

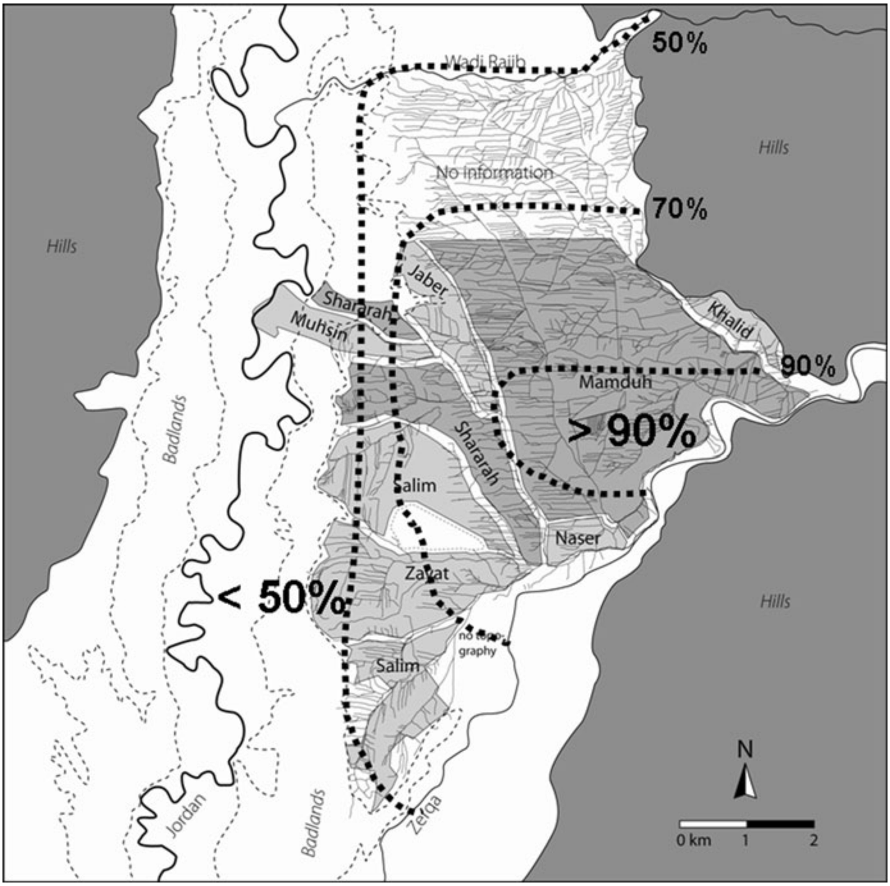

Fig. 8 Indicative certainty of canal water delivery (adapted from Kaptijn, this issue)

of the clans along the irrigation channels suggests that the Manduh and Shararah clans were potentially dominant as all other clans were located downstream.

The modeling results suggest that there is differential security in water delivery between clans, but also within areas dominated by a single clan. Although much detail is not known, these potential material inequalities were most likely countered in social arrangements, as clans were part of the Musha' system. The article of Kaptijn in this issue discusses these arrangements in much more detail, but basically fields rotated among clan members every few years. Strictly speaking, the modeling presented above is restricted to the canal system of the early 20th century. The same canal system may have been in use during the Mamluk period, but from Kaptijn's article it becomes clear that agricultural arrangements of this period—with its centrally controlled sugar cane production—would suggest central irrigation arrangements as well. It is likely, however, that a canal irrigation system with canals following comparable routes through the plain existed in the Iron Age II period (1000–540 BC) (Kaptijn, this issue; Kaptijn 2009). Such a system would have to deal with similar upstream–downstream patterns as found in the modeling. It is less likely that canal irrigation was applied in the Early Bronze Age (3600–2300 BC). The Zerqa triangle was quite densely occupied as well, and the climate was probably slightly more humid, but not so much that crops could be sustained by rainfall only. As rivers and wadis were at that time not as deeply incised as today, they would have submerged the area regularly. Early Bronze Age communities may have practiced farming in the floodplains of the Zerqa (Kaptijn 2009). Flood irrigation, however, would have to be associated with quite different upstream–downstream relations compared to canal irrigation.

Outlook

The three cases discussed do show that spatial position in an irrigation system, social arrangements, and water availability are linked. In the modern system of Arequipa, the upstream water users may not be stimulated to organize, but nevertheless they do influence the options for their downstream colleagues. The irrigators at Alto Cural, being most downstream, appear to lack access to enough irrigation water. In contrast to others, these irrigators have not been able yet to change their disadvantaged position to a better one. Elsewhere I discussed a situation in Argentina, where the downstream farmers were the ones in control over the canal, and where these downstream farmers had secured their access to water (Ertsen and Van Nooijen 2009). In the Pampa de Chaparrí, the evidence found on canal and field layouts in combination with the hydraulic modeling suggests a clear upstream–downstream pattern, with higher and better controllable water use upstream compared to downstream. An interesting difference with the Arequipa situation is that the most downstream area on the Pampa still seems to have been farmed. This suggests that a water source was available, as natural rainfall cannot sustain agriculture. If the water did not come from canals, it is not unlikely that groundwater—perhaps even coming from access irrigation water upstream—was the source sustaining agriculture. In the final case of Jordan, again an upstream–downstream pattern could be linked to positions of groups of water users within the system. As Kaptijn discussed in this volume, in Jordan disadvantageous positions were compensated through social arrangements.

Human actions, hydrological realities, and hydraulic properties of irrigation system create patterns of upstream–downstream water use. These patterns are very often both idiosyncratic and unpredictable, although it is clear that in gravity irrigation one would expect upstream uses to have a starting advantage. Irrigation as agricultural practice is as much about manipulating water flows in short-time periods of hours and days as it is about balancing water volumes over time periods of months or even seasons. It is perfectly possible to determine how much water would be needed to grow crops within irrigation systems per season. It is also possible to determine water availability in the same season. It is vital, however, to include in the analysis how each and every day irrigators have to work hard to bring this water to their fields. Daily activities are shaping irrigation [compare with the concept of labor-tasking as discussed by Scarborough and Lucero (this issue)]. Results of the short-term manipulations by individual agents may be expressed in effects on different and usually larger temporal and spatial scales influencing complete societies. Understanding irrigation system development in archaeology should explicitly link the stochastic nature of water availability on different time scales, varying from flows in periods of hours to volumes in periods of years and decades, to short and long term human responses to this stochastic nature, from individuals to societies. The calculations and modeling discussed above are still relatively simple, but do show that it is worthwhile to develop such a modeling-based approach to generate the flows and balances in ancient irrigated environments, as it yields new insights in the way irrigation has succeeded in sustaining human civilization—or failed to do so.

References

Adderly WP, Simpson IA (2006) Soils and palaeo-climate based evidence for irrigation requirements in Norse Greenland. J Archaeol Sci 33:1666–1679

Altaweel M (2007) Investigating agricultural sustainability and strategies in northern Mesopotamia: results produced using a socio-ecological modeling approach. J Archeol Sci 34:1–15

Carlstein T (1982) Time resources, society and ecology. On the capacity for human interaction in space and time, Volume 1: pre-industrial societies. Allen and Unwin, London

Christiansen JH, Altaweel M (2006) Simulation of natural and social process interactions: an example from Bronze Age Mesopotamia. Soc Sci Comput Rev 24:209–226

Eling HH (1987) The role of irrigation networks in emerging societal complexity during late preHispanic times: Jequetepeque Valley, north coast, Peru (volumes I and II). PhD Thesis, University of Texas, Austin

Ertsen MW, Van der Spek J (2009) Modeling an irrigation ditch opens up the world. Hydrology and hydraulics of an ancient irrigation system in Peru. Phys Chem Earth 34:176–191

Ertsen MW, Van Nooijen R (2009) The man swimming against the stream knows the strength of it. Hydraulics and social relations in an Argentinean irrigation system. Phys Chem Earth 34:2000–2008

Farrington IS (1980) The archaeology of irrigation canals, with special reference to Peru. World Archaeol 11:287–305

Giddens A (1984) The constitution of society: outline of the theory of structuration. Polity Press, Cambridge

Hayashida FM (2006) The Pampa de Chaparrí: water, land, and politics on the north coast of Peru. Lat Am Antiq 13:243–263

Herhahn CL, Hill JB (1998) Modeling agricultural production strategies in the northern Rio Grande Valley, New Mexico. Hum Ecol 26:469–487

Hunt R (1988) Size and the structure of authority in canal irrigation systems. J Anthropol Res 44:335–355

Hunt CO, Gilbertson DG, El-Rishi HA (2007) An 8000-year history of landscape, climate, and copper exploitation in the Middle East: the Wadi Faynan and the Wadi Dana National Reserve in southern Jordan. J Archeol Sci 34:1306–1338

Janssen MA, Anderies JM (2007) Stylized models to analyze robustness of irrigation systems. In: Kohler TA, Van der Leeuw SE (eds) 200 The model-based archaeology of socionatural systems. School for Advanced Research Press, Santa Fe, pp 157–173

Kaptijn E (2009) Life on the watershed. Reconstructing subsistence in a steppe using archaeological survey: a diachronic perspective on habitation in the Jordan Valley. Sidestone Press, Leiden

Keller J (1986) Irrigation system management. In: Nobe KC, Sampath RK (eds) 1986 Irrigation in development countries. Westview Press, Boulder
Kohler TA, Van der Leeuw SE (eds) (2007) The model-based archaeology of socionatural systems. School for Advanced Research Press, Santa Fe
Koopman EE (2009) The influence of hydraulics and spatial differences on the daily practice within an irrigation system. A case study in Arequipa, Perú, MSc Thesis, Delft University of Technology
Kosok P (1965) Life, land, and water in ancient Peru. Long Island University Press, New York
Lansing JS, Cox MP, Downey SS, Janssen MA, Schoenfelder JW (2009) A robust budding model of Balinese water temple networks. World Archaeol 41:112–133
Levine G (1980) The relationship of design, operation and management. In: Coward EW (ed) Irrigation and agricultural development in Asia: perspectives from the social sciences. Cornell University Press, Ithaca, pp 51–62
Netherly PJ (1984) The management of late Andean irrigation systems on the north coast of Peru. Am Antiq 49:227–254
Nordt L, Hayashida F, Hallmark T, Crawford C (2004) Late prehistoric soil fertility, irrigation management, and agricultural production in northwest coastal Peru. Geoarcheology 19:21–46
Ortloff CR (2009) Water engineering in the Ancient World. Archaeological and climate perspectives on societies of ancient South America, the Middle East, and South-East Asia. Oxford University Press, Oxford
Ortloff CR, Feldman RA, Moseley ME (1985) Hydraulic engineering and historical aspects of the pre-Columbian intravalley canal systems of the Moche Valley, Peru. J Field Archaeol 12:77–98
Scarborough VL (2003) The flow of power. Ancient water systems and landscape. SAR Press, Santa Fe
Scarborough VL, Isaac B (eds) (1993) Economic aspects of water management in the prehispanic new world, Research in Economic Anthropology, Supplement 7, JAI Press, Greenwich, pp 17–69
Sewell WH (2005) Logics of history, social theory and social transformation. Chicago Studies in Practices of Meaning, Chicago
Soja E (1985) The spatiality of social life: towards a transformative retheorisation. In: Gregory D, Urry J (eds) 1985 social relations and spatial structures. Macmillan, London, pp 90–122
Téllez S, Hayashida F (2004) Campos de Cultivo Prehispánicos en la Pampa de Chaparrí. Bol Arqueol PUCP 8:373–390
Uphoff N, Wickramasinghe MI, Wijayaratna CM (1990) "Optimum" participation in irrigation management: issues and evidence from Sri Lanka. Hum Organ 49:26–40
Van der Kooij G (2007) Irrigation systems at Dayr 'Alla. In: Al-Khraysheh F (ed) 2007 Studies in the history and Archaeology of Jordan IX. Department of Antiquities, Amman, pp 133–144
Vos J (2002) Metric matters: the performance and organisation of volumetric water control in large-scale irrigation in the North Coast of Peru, PhD Thesis, Wageningen University
Whitehead PG, Smith SJ, Wade AJ, Mithen SJ, Finlayson BL, Sellwood B, Valdes PJ (2008) Modelling of hydrology and potential population levels at Bronze Age Jawa, northern Jordan: a Monte Carlo approach to cope with uncertainty. J Archeol Sci 35:517–529
Widgren M (1979) A simulation model of farming systems and land use in Sweden during the early Iron Age, c. 500 b.c.–a.d. 550. J Hist Geogr 5:21–32
Wilkinson TJ (2003) Archaeological landscapes of the Near East. University of Arizona Press, Tucson
Wilkinson TJ, Christiansen J, Ur JA, Widell M, Altaweel M (2007a) Urbanization within a dynamic environment: modelling Bronze Age communities in upper Mesopotamia. Am Anthropol 109:52–68
Wilkinson TJ, Gibson M, Christiansen J, Widell M, Schloen D, Kouchoukos N, Woods C, Sanders JC, Simunich K-L, Altaweel M, Ur JA, Hritz C, Lauinger J, Paulette T, Tenney J (2007b) Modeling settlement systems in a dynamic environment: case studies from Mesopotamia. In: Kohler TA, Van der Leeuw SE (eds) 2007 The model-based archaeology of socionatural systems. School for Advanced Research Press, Santa Fe, pp 175–208
Wittfogel K (1957) Oriental despotism. A comparative study of total power. Yale University Press, New Haven

Author Biography

Maurits Willem Ertsen is senior lecturer within the Water Resources Management group of Delft University of Technology. Having a background in irrigation engineering, he has extensive experience with historical/archaeological research, irrigation design and management and practices of learning processes in water management.