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Hydraulic landscapes in Mesopotamia: the role of human niche construction

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Abstract Human niche construction emphasizes the capacity of organisms to modify their environment and thereby influence their own and other species' evolution. For the hydraulic landscapes of southern Mesopotamia we employ geoarchaeological data, remote sensing and ancient texts to suggest that major irrigation systems in the central Mesopotamian plains were a form of herringbone system and that they developed through human niche construction as a result of the elaboration of crevasse splays along raised levees. The remarkable duration of these systems (some 4000 plus years) suggest that (a) they were sustainable over many millennia and (b) the short component canals could be managed by small lineages. However, equally they could be brought under the administration of the state.

Keywords Human niche construction · Irrigation · Mesopotamia · Sustainability

Introduction: concepts and definitions

Irrigation and water supply systems can vary from major canals dug under imperial or kingly authority down to small-scale systems which are more piecemeal, organic features

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with no obvious guiding hand; but there is not always a direct relationship between scale and the amount of power implemented. In Mesopotamia, where irrigation canals structure the landscape, it is easy to assume that the former predominate, however, for many canal systems it is difficult to infer how they originated or were administered. In this article, we explore the contribution of small-scale processes to Mesopotamian hydraulic landscapes, specifically as they may have contributed to the development of a distinctive form of canal system, namely the pattern of herringbone canals and fields. No attempt is made to discuss the history, development or practices of Mesopotamian irrigation, which have been covered by Adams (1981), Pemberton et al. (1988), Postgate (1994, pp. 173–190), Charles (1988); Bagg (2012), Widell et al. 2013). Rather we provide evidence for certain types of hydraulic landscapes which may have been formed by processes of human niche construction, and which, in turn, may have contributed to long-term developments of irrigation systems.

Archaeology is particularly well suited to the investigation of such water systems, because the associated sites and geoarchaeology enable the duration of channel systems to be estimated, and by extension their long-term sustainability.

Here we specifically refer to the landscapes of southern Mesopotamia as hydraulic landscapes, because water is the specific structuring agent in what is actually a complex array of rivers, canals, distributaries and marshes which dominate and in part create the landscape. However, western classifications of waterways are not entirely applicable to those of Mesopotamia because, "..the local inhabitants do not differentiate between natural streams and canals (which are both referred to as shatts)….." (Cotha Stage III final report, pp. 18–19).[1]

The following definition provides a hint of how human niche construction can be applied to hydraulic landscapes:

> Humans, like beavers and termites, are vigorous practitioners of what biologists call 'niche construction': the active modification of their habitat, which can alter the selection pressures on behaviour through feedback relationships. (Lansing and Fox 2011, p. 927).
>
> Also:
>
> Niche construction theory….originated as a branch of evolutionary biology that emphasizes the capacity of organisms to modify their environment and thereby influence their own and other species' evolution. Kendal et al. (2011, p. 785).

Kendal and colleagues emphasize that the key feature of human niche construction (or HNC) is not the modification of environments per se, but that organisms induce changes in the selection pressures in environments (Kendal et al. 2011, p. 785; also Odling Smee et al. 2003). However, applying the concepts of niche construction to the Mesopotamian landscape requires something of a leap of faith, and although the explicitly genetic aspects of this conceptual framework are touched upon in the discussion, we mainly concentrate on how human niche construction can be applied at a general level to the development of Mesopotamian irrigation systems, as well as some of the consequences of those actions.

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[1] Nevertheless, current Iraqi usage normally uses shatt to refer to the main "natural" channel as in Shatt al-Furat; Jadwal is employed to large canals usually mechanically excavated; sajiyah, naher or tubber refer to smaller canals excavated by hand. Alternatively, in standard Arabic nahar refers to the "natural channel" or qanat to larger mechanically excavated canals; saqiyah being reserved for small hand dug canals. Thus, modern usage does differentiate between artificial and natural channels, although it would seem that local farmers do not necessarily make such distinctions.

Before discussing the application of HNC to irrigation systems in formal terms, it is useful to consider how Mesopotamian farmers (in this case in the southern plains) dealt with the challenges of irrigation:

> “The ancient traditional methods employed by the farmers to use the water, and especially those of the Gharraf system, are not very effective when considered individually. However, all that has to be done is to make natural streams with unstable courses flow in directions which are useful to the farmer. When this is done on a large scale with a skill born of long experience, such methods become effective and leave a characteristic deep seated mark on the alluvial landscape.” “……the close attention paid by farmers to natural tendencies is aimed at making the best use of what is available. In this way they do not work against nature and may be considered to ‘catalyse’ phenomena which were originally unstable.” Cotha Stage III final report, pp. 18–19.

This is echoed by a local idiom in southern Iraq: “la twajih al-maay ala alwah” which means in English: do not dig a canal against the gradient. This idiom is used to describe the situation where someone makes a suggestion of an impossible task.

Mesopotamian hydraulic landscapes

The broad geosyncline that forms the Mesopotamian Plain is infilled by a complex of Plio-Pleistocene and Holocene fine sediments from several sources: the Zagros Mountains to the east, episodic wadis draining from the desert to the west (the largest being the Wadi al-Batin), and the huge perennial rivers of the Tigris and Euphrates which drain the broad arc of the mountains to the north, northeast and northwest; in addition, the SE regions have

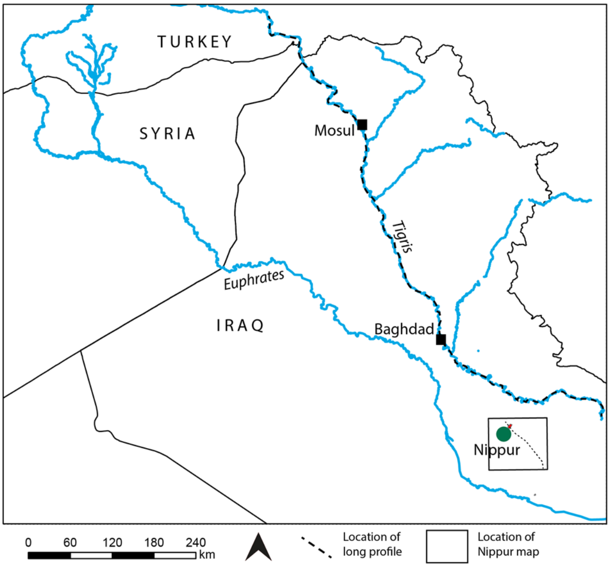

Fig. 1 Regional map of upper and lower Mesopotamia showing location of the Nippur Third River Drain case Study and the longitudinal profile on Fig. 2 (by Louise Rayne)

Table 1 Range of gradients of the flood plain in the Gharraf East Area, near Tello-Girsu (from Cotha Consulting Engineers 1959. Vol. II (2) p. 14 Table A. VIII-1)

Orientation of gradient	Mean regional gradient	Range of gradients
Longitudinal (over 130 km)	0.05/1000 (1: 20,000)	0.04/1000 (1: 25,000) to 0.45/1000 (1:2222)
Transverse (gradients for main channel levees)		
Gharraf (1500 m)	2/1000 = 1: 500	
El Amah (1700 m)	1.4/1000 = 1: 714	
Shattrah (3200 m wide)	0.8/1000 = 1: 1250	

accumulated a deep sequence of brackish-marine deposits from the early Holocene marine transgressions (for summaries of the physical geography see Yaqoub 2011; Pournelle 2013). Of these sources, the Tigris and Euphrates rivers, when they reach the Mesopotamian Plains, form branching, anastomosing systems which both dominate and structure the southern landscape (Adams 1981; Wilkinson 2003; Fig. 1).

In the southern Mesopotamian plains the rainfall, which is less than 200 mm per annum, is insufficient for rain-fed agriculture. Therefore irrigation is essential. Also critical is that the excavation of canals of sufficient gradient to allow water to flow without excessive sedimentation or erosion is not as easy as it seems because much of the terrain slopes at gradients of less than 1:5000, frequently, in the south, as little as 1:10,000 (Fig. 2; Table 1). Because irrigation canals require an ideal gradient of around 1:1000 in order conduct water so that it neither deposits sediment nor erodes the channel bed, the limitations of gradient raise some problems. Where the gradient of the terrain exceeds 1:1000 canals can be used to guide water away from the main trajectory of the canal, but at greater gradients the high speeds of flow can be difficult to control and often require temporary bunds to slow the flow. On the other hand, although gradients less than this can be used, they can result in increased sedimentation, especially in muddy rivers like the Tigris and Euphrates. In the Mesopotamian plains, if canals are constructed at gradients less than 1:4000, and if they are to transport water from levels of 1–2 m below the plain, water either needs to be raised by means of temporary bunds (Postgate 1994, p. 177; Rost et al. 2011) or it will take a considerable distance for the canal to "catch up" with the plain level so that the water can be raised to a sufficient level to be re-distributed for irrigation.

Early irrigators therefore operated under a number of constraints. As illustrated on Fig. 2, in the northern parts of the basin (Upper Mesopotamia) gradients of the terrain are sufficiently high to enable irrigation canals to be dug and constructed across the landscape; consequently there is a considerable degree of flexibility for water distribution. However, in Upper Mesopotamia, where irrigation is relatively easy, it is less fundamental to daily life because much of the region receives sufficient rainfall for rain-fed cultivation to prevail.[2] On the other hand, where irrigation *is* necessary, namely in the southern plains below Baghdad (Lower Mesopotamia), the low gradients of the terrain make the construction of canals much more difficult.

To be enduringly successful, irrigation systems need to take into account the geomorphology of the terrain. In southern Mesopotamia, during flooding seasons, a river overflows

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[2] However, Upper Mesopotamia became the locus for the expansion of irrigation after around 1200 BC (Wilkinson and Rayne 2010).

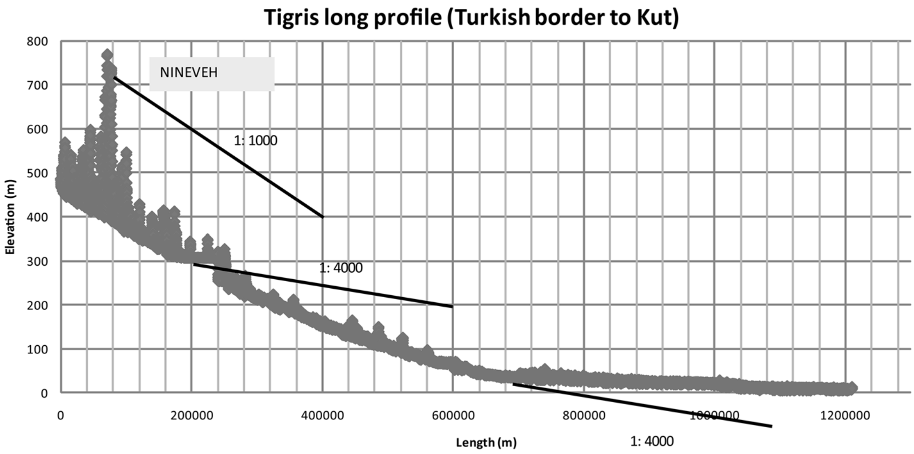

Fig. 2 Long-profile of Tigris River generated from SRTM digital elevation model. Deviations from the main profile in the area around Nineveh result from where the profile line cuts through minor hills and watersheds (by L. Rayne). Slopes of 1: 1000 and 1: 4000 indicated for comparison

its banks so the coarsest sediment will deposit at channel edges while fine sediments will deposit in the floodplain. Consequently, natural levees will be built up gradually by many floods. The rivers not only adopt a bifurcating course (forming anastomosing channels), they end to flow along the crests of low levees, that are between 1 and 5 m above the level of the flood plains. As noted by Robert McCormick Adams it was therefore possible to direct irrigation waters down the levee slopes at a steeper gradient (Adams (1981, p. 8). This is illustrated on the block diagram (Fig. 3) which is based on actual gradients in the southern plains (Wilkinson 2013; Table 1). This simple but ingenious approach appears to have resulted in one of the characteristic features of the Mesopotamian landscape, namely the creation of the so-called herringbone pattern of irrigation canals and fields (Fig. 4). Although, not necessarily the dominant feature of the Mesopotamian hydraulic landscape (especially in the modern day when many major institutional irrigation systems appear to have disregarded many of the limitations and advantages of the terrain), herringbone field patterns are common in both the north and the south of the plains. Here, using first principles and concepts of human niche construction, we consider how such a pattern may have developed and what its consequences may have been.

Human niche construction applied to southern Mesopotamia

Concepts of human niche construction provide a useful way of viewing the development of small-scale water management systems. For example, in the early Holocene human niche construction arguably operated where small-scale communities built upon naturally occurring conditions to divert water to nearby localities, with the result that incipient water management then created the conditions for future developments. This is well exemplified in the hills of Baluchistan and Khyber Pakhtunkhwa in the Upper Indus region where early farmers tended crops on alluvial fans and probably enhanced the natural processes of irrigation by constructing earth barriers to intercept and divert flows (Petrie and Thomas 2012; also Sherratt 1980 for the Middle East).

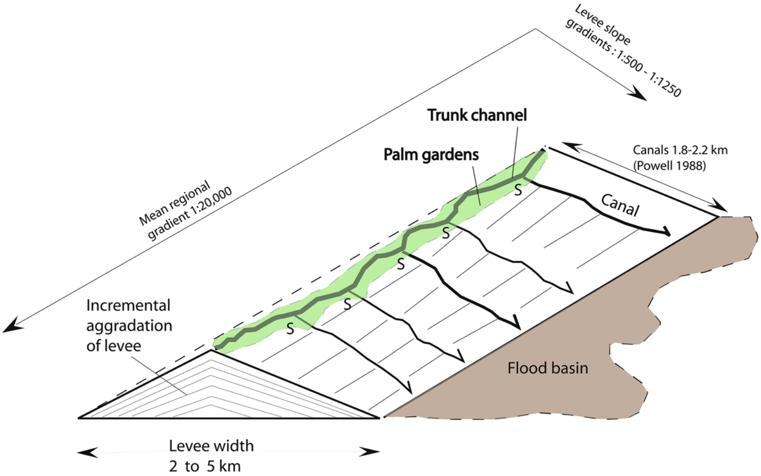

Fig. 3 Block diagram of levee irrigation system based upon slope gradients in the southern Mesopotamian plains (based upon Cotha Consulting Engineers 1959, Table A. VIII-1)

Fig. 4 Herringbone pattern of fields in the western plains showing the canals on raised ground and the basin soils between. Note occasional areas of salinization around some basin areas (by Jaafar Jotheri)

In his classic volume on the soils of Iraq, Buringh suggested:

> A very primitive system of irrigation consisting of a short cut in the river banks was probably the first step. This system has gradually been developed into a canal system and finally into a controlled canal irrigation system on the delta and flood plain. Buringh 1960, p. 255).

However, rather than see the levee slopes as forming the focus of this early form of irrigation, Buringh argued that the basin soils were most suitable for irrigation as they were

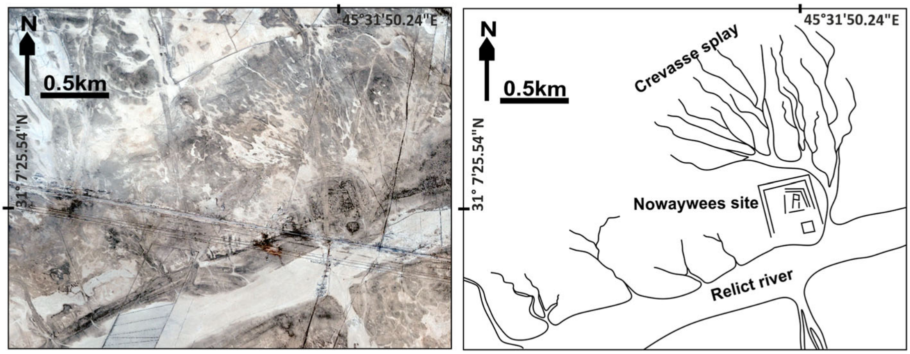

Fig. 5 Crevasse splay from relict channel with adjacent archaeological site in the western plains of southern Iraq (Jaafar Jotheri)

watered naturally by uncontrolled flood irrigation through flood gullies (Buringh 1960, p. 152).[3]

This levee-break model can be extended and formalized because a key feature of major Mesopotamian channels is that they are raised on levees and that levee breaks can occur either as a result of natural causes or human actions. As a result, the small distributaries so created would form a minor fan of sediment, known as a crevasse splay (Fig. 5). These are common features of many alluvial lowlands (Florsheim and Mount 2002, pp. 67–94; Verhoeven 1998; Wilkinson 2003, p. 88, Fig. 5.9; Yaqoub 2011, Fig. 5) where they can act as a focus for irrigation. The water issuing from crevasse splays could have supplied small irrigated patches of land which would have formed ideal niches for a household or two (Fig. 6 a, b T1). However, by exerting further control of the levee break, the discharging flow could have serviced extended lineages (Fig. 6, T2 and T3), until each branch became a formal distributary, positioned approximately vertically to the main channel. Traditional practice in Iraq suggests that where levees were lower, around 2 m high, the flow from levee breaks was easier to control, whereas where they were high, maybe 5–7 m elevation, the issuing discharge was more difficult to control. This means that farmers often choose to irrigate areas where the levees and topographic elevations are lower.[4]

One advantage of levee slope irrigation is that by taking advantage of flow down the levee slope, these channels would have made it easier to direct flow in various directions into fields and they would have incurred less sedimentation. Nevertheless, because the levee break would represent a point of weakness in the levee bank this could result in larger flows breaking through to create major distributary channels and eventually avulsions (i.e. channel shifts: Wilkinson 2003, pp. 88–89; Makaske 2001; Heyvaert et al. 2012, Fig. 10). However, if managed with care the distributaries of simple levee breaks would then provide ideal loci for irrigated fields, which could eventually be formalized into a more regular trellis of irrigation canals (Fig. 7). Not only is the topology of the natural crevasse splay junction the same as that of the formalized system (Figs. 6, 7), but also, the fields of the latter can be shown to have been of roughly the same scale as the Sumerian features (Widell et al. 2013, pp. 68–74).

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[3] Although sometimes farmers irrigate basin soils to encourage the growing of aquatic plants to feed cows or buffalo.

[4] Reported to Jaafar Jotheri by his grandfather who chose to irrigate land around the lower relief Najaf marshes rather than the higher relief terrain close to Hilla.

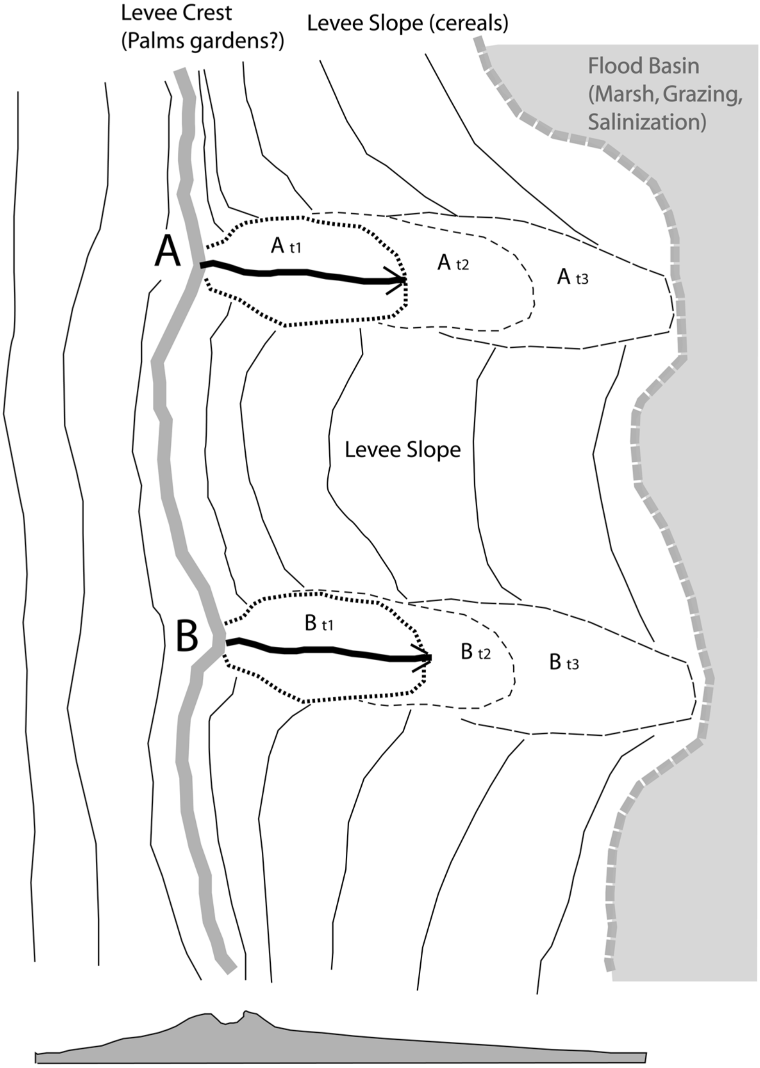

Fig. 6 Initial crevasse splay irrigation system

Therefore although there is no direct field evidence to demonstrate such an evolutionary sequence, geomorphic analogy, topology, modern field patterns and channel form, together all suggest the feasibility of such a development. Moreover, the geometry of Sumerian irrigation channels (Rost 2011) also supports the suggestion that herringbone systems were in existence back to at least the third millennium BC.

Once a crevasse splay was established, either by human or natural agency, the initial process of interception could have been modified to provide a more formalised pattern. In other words: “One generation does things in a certain way, and the next generation, instead of starting from scratch, does them in more or less the same way, except that perhaps it adds a modification or improvement. The succeeding generation then learns the modified

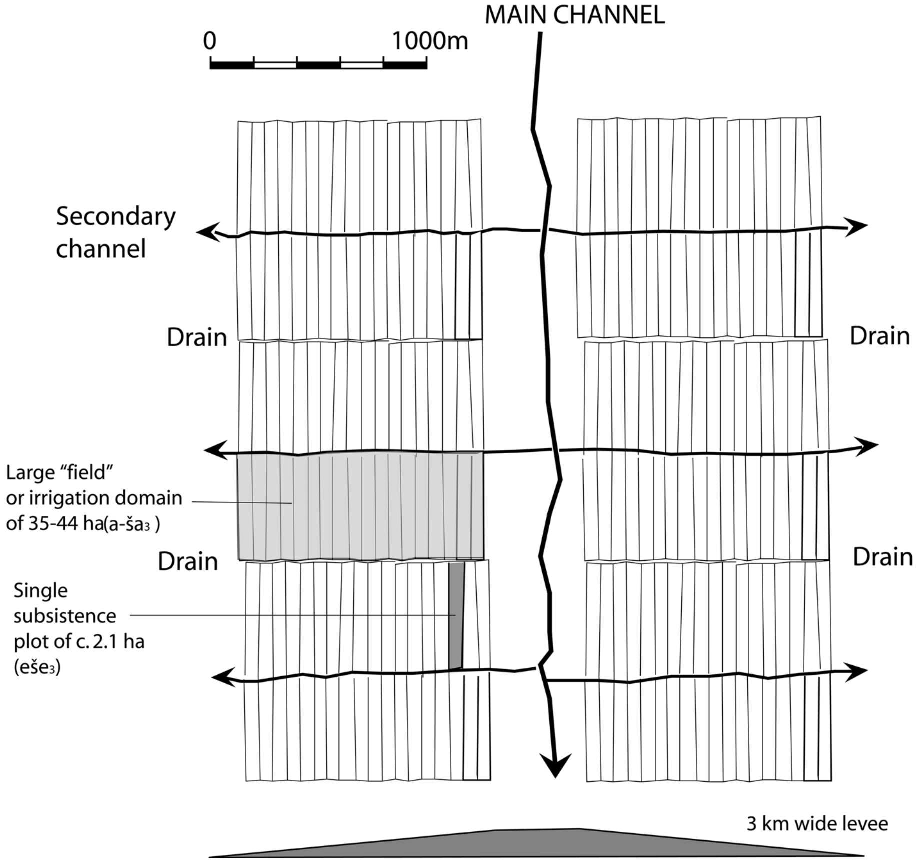

Fig. 7 Diagrammatic layout of trellised field systems (Widell et al. 2013)

version, which then persists across generations until further changes are made" (O'Brien and Laland 2012, p. 437; citing Tennie et al. 2009). Such processes of generational copying can be suggested to have operated in crevasse splays in southern Mesopotamia, specifically where the secondary channel had become managed by local communities and modified incrementally over succeeding generations.

By adopting these practices, not only would early irrigation systems have developed in high risk environments, if early communities chose to create gaps in the levees to "manage" the flow from the natural levee breaks and irrigated patches of soil, their innovations could also lead to the development of river diversions (Heyvaert et al. 2012, Fig. 10). These could then form a sequence of evolutionary development of managed water distribution (Wilkinson 2003, Fig. 5.9). Early communities in Mesopotamia therefore appear to have lived on the cusp between successful management and engineered disaster, and this creative tension may have formed a crucial aspect of human niche construction in the region. Unfortunately, because of the constant processes of sedimentation and wind erosion operating in southern Mesopotamia there is no strong evidence for early prehistoric crevasse-splay agriculture, nor its scaling up into larger scale irrigation systems.

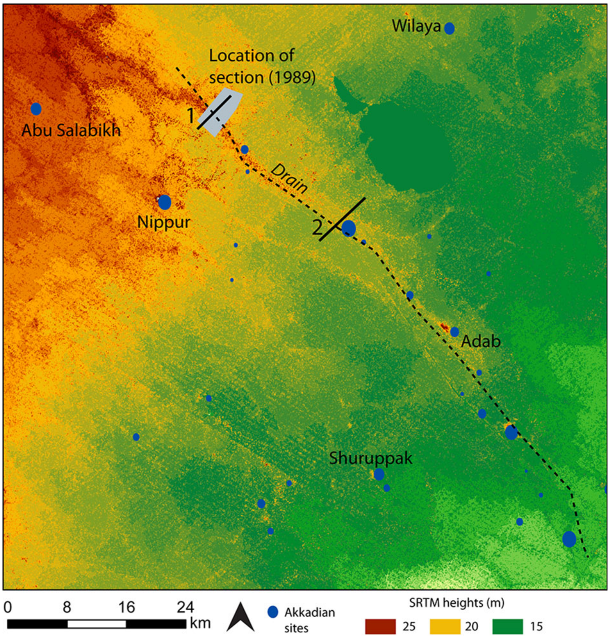

Fig. 8 SRTM topographic map of third River Drain near Nippur; *1* cross profile of levee to north at 1; *2* cross profile at 2 (by Louise Rayne)

Nevertheless, the central Mesopotamian plains provide a compelling example of a major levee-based herringbone system of irrigation that persisted for some 5000–6000 years.

Case study

The central Mesopotamian plains near Nippur were originally surveyed by Robert McCormick Adams, whose maps demonstrate that archaeological sites of third millennium BC and later date formed alignments along what were inferred as former channels and canals (Adams 1981; Adams and Nissen 1972; see also Jacobsen 1960). Subsequently, using SRTM-generated digital elevation models, these sites have indeed been shown to have been associated with topographic levees of major channels (Hritz 2004, 2010, pp. 190–192; Hritz and Wilkinson 2006). Specifically, Adams identified a major watercourse which could be followed through the central plain from the east of Kish in the north to Tell Jidr or Adab to the SE (Adams 1981, Fig. 27; Hritz 2010, Fig. 5; Ur 2013, Figs. 7.5, 7.6). This levee complex, which is also evident on SRTM images of the area (Hritz 2010, Fig. 5; Fig. 8), was cut in 1989–1990 by engineers authorised by Saddam Hussein (i.e. the Third River Drain; Mirak-Weissbach 1993), and a rapid assessment was made by the author and McGuire Gibson in spring 1989 (Wilkinson 2003, pp. 78–79).

The 5.8 m sequence of fine-sediments exposed to the northeast of Nippur (Fig. 8) shows a complex sequence of sediments through an aggrading levee as follows (Fig. 9):

- at the base, sedimentary accumulation commenced with a blocky clayey silt of a relict flood plain soil horizon. This included at ca. 4.2–4.5 m depth a cultural horizon

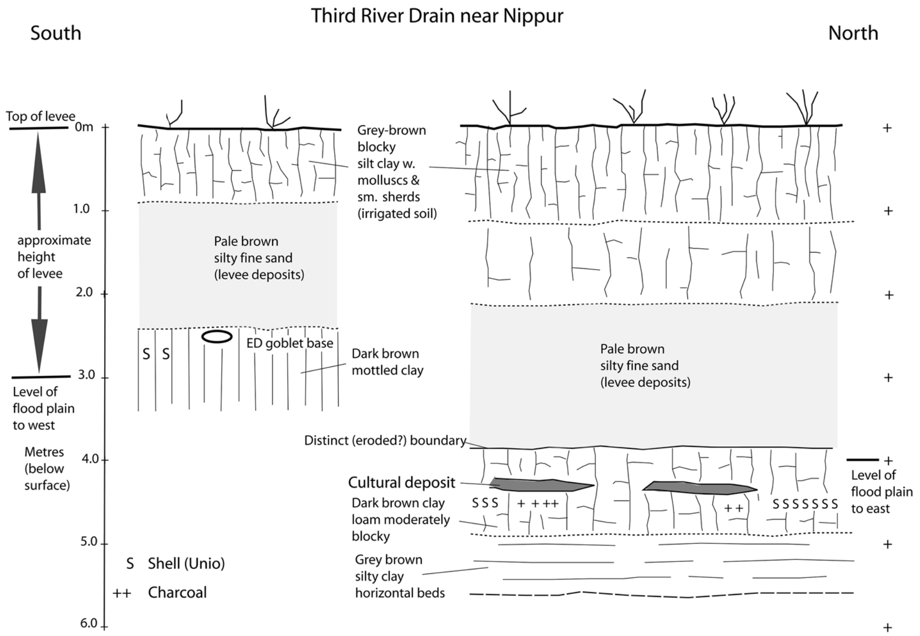

Fig. 9 Two sections through the third River Drain near Nippur (for location see Fig. 1). The cultural deposit in the *right hand* section contained a clay sickle, ca. 4000–3000 BC and the Early Dynastic (ED) goblet base in the *left* hand figure dates to around 2900–2500 BC. The *grey brown blocky* "irrigated soil" at the *top* of both sections contained occasional calcium carbonate or calcium sulphate veins and very fine sherd fragments, dated in other sections in the area by occasional Sasanian-Early Islamic sherds; also present were shells of the mollusc Mellanoides

containing occasional potsherds and a baked clay sickle of Ubaid or Uruk date (ca. 4500–3200 BC). To the south, a similar horizon included an Early Dynastic goblet dated in the range 2900–2500 BC.

- This was overlain by some 1.4–1.75 m of fine sandy loam and sandy silt of levee deposits which became progressively finer upwards (cf. soils of river levees in Buringh 1960, p. 148).
- Finally the top of the sequence consisted of about 1 m of grey-brown blocky silty clay containing freshwater gastropods and small fragments of ceramics. This appears to have been a Sasanian and Early Islamic irrigated soil horizon. According to Buringh (1960, p. 155), irrigated soils have a rather uniform texture because of the fairly even flow of the canals which deposit most of the fine sand within the first kilometre of the canals, with silt and clay being deposited in the more distal parts of the canal and the irrigated fields. River levees often consist of several layers of different sediments with thick layers of fine sand usually fining upwards followed by thin layers or lenses of silts. Irrigation canals may disrupt deposits as the higher stream velocity in the canals transport sand particles further afield.

The chronological development of the levee is framed by two cultural horizons: at the base by the thin band of occupational debris, the clay sickle and an Early Dynastic goblet base to the south; in the upper horizons, by occasional Sasanian Early Islamic sherds. These provide an estimated sedimentation rate of 0.73 mm per annum for the north section (to right, Fig. 9) and 0.51 mm per annum (to left), which fits into overall sedimentation rates estimated for the Mesopotamian plains computed from the data of Clemens Reichel, namely: 1.35 mm/per annum for the Diyala region, 0.74 for near Nippur and 0.2 mm/p.a. for the southern plains (Wilkinson 2003, p. 80).

Overall, it appears that the levee started to accumulate either shortly after the Ubaid/Uruk period (ca. 4500–3200 BC) in one section, or 2900–2500 BC in another section, and that deposits proximate to the main channel (i.e. the fine sandy loams) were deposited initially, to be replaced by progressively finer irrigated soils (with increasingly blocky and clay/silt rich soils) towards the top, perhaps as the main channel migrated laterally.

The above sequence is now supported by two radiocarbon dates from sediments deposited towards the base and top of the sequence downstream along the same levee complex, to the southwest of Adab (Fig. 8).[5] The lower sample supplied a date estimate of 4040–3955 Cal BC (Cal BP 5990–5905, 2 sigma calibration; Beta—379039); and the upper of Cal AD 1410–1445 (Cal BP 540–505) (Beta—379038). Of these the earlier falls within the expected date range of the clay sickle from Nippur Third River Drain section, whereas the latter falls within Adams' Late Islamic period, corresponding to the Ilkhanid and later periods (1256–1353 AD and slightly later) when the irrigation systems of the central plains were either abandoned or in the process of being abandoned (Adams 1981, pp. 220–223).

By use of GIS, the aggraded levee sequence can be seen to compare closely with the distribution of mid-third millennium BC (Akkadian) archaeological sites derived by Adams (1981) and indicated, together with the line of the Third River Drain, on Fig. 8. Both the alignments of sites and their dates of occupation demonstrate that this levee and the sites along them were in use during the Late Early Dynastic, Akkadian, Ur III/Isin-Larsa, Cassite, Neo-Babylonian/Achaemenid; Seleucid/Parthian, Sasanian, Early and Middle Islamic, and less certainly during the Uruk, Jemdet Nasr, Early Dynastic I, Old Babylonian, and Middle-Babylonian periods (Adams 1981). The levee was abandoned or hardly in use during the Late Islamic period, but significantly it was then taken advantage of again by the engineers of the Third River Drain (Fig. 8). Taking a conservative date for the initiation of the levee (mid-third millennium BC from the ED goblet) and combining it with the evidence from the associated sites, it seems that the levee was in use for water supply and irrigation for some 3500 years, that is if it ceased to be in use in the Middle Islamic period. If the initiation of the levee is taken from the radiocarbon date at Adab, the clay sickle and the evidence of Uruk period sites along the levee (Adams 1981, Figs. 12, 13 and 18), then the duration of the levee and associated irrigation systems may have been as much as 5500 years.

During its later phases, the hydraulic system NE of Nippur consisted of a central longitudinal channel and "spur" canals of modest length which took advantage of the levee slope to deliver water at right angles to the main channel (Wilkinson et al. 2012, p. 170). While it can take some time for a new channel to have suitable elevation for irrigation, within tens of years the levee can be significantly higher than the surrounding area. Although there is no evidence for the spur canals during the earlier phases, they are suggested for the Sasanian period (Adams 1981, Fig. 44). Here, the major feature is that the spur canals appear to have become elongated, presumably as the amount of irrigated area was extended on to the lower levees and flood basins, but they have retained their distinctive herringbone form (Fig. 10).

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[5] This sequence, sampled by Jaafar Jotheri, appears to be part of a shallower sequence in the distal part of the levee; more details of the sedimentary context will be presented in the author's Ph.D. thesis and a future publication.

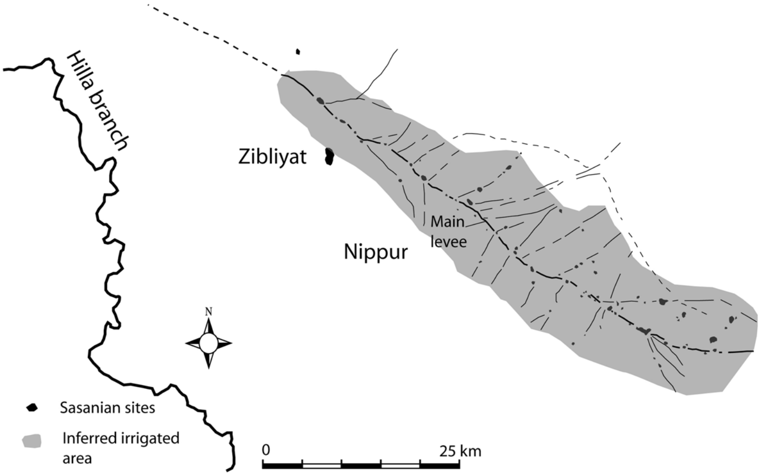

Fig. 10 Sasanian period herringbone pattern of canals and sites for the central Mesopotamian channel complex (re-drawn from Adams 1981, Fig. 44)

Textual evidence and canals

Overall, the considerable time span of its use (ca. 4000 years), whether intermittent or continuous, together with the continuation of small-scale irrigation practices along the spur canals, suggests that the overall irrigation network developed out of a system that was very similar to that of the Sumerian "short canal" system as discussed by Rost (2011).

Because of the gentle gradients of the plain, Sumerian communities had the choice of digging canals up to 40 km or more in length (Hunt 1988, p. 194), but with extremely gentle gradients, or much shorter canals from the main channels down the slope of the significantly steeper slopes of the levees (Table 1; Fig. 3). Because evidence from cuneiform texts suggests that most canals were of modest scale (Powell 1988; Civil 1994), it seems that the latter class of canals predominated, although longer canals certainly were dug. Thus Powell estimates that the most frequent length of canals was between 1.8 and 2.2 km. These figures, when doubled to account for flow from both sides of a levee amount to roughly the width of typical levees (3.6–4.4 vs. 2–5 km) (see Wilkinson 2013, with references). In other words, as with many traditional irrigation patterns, rather than digging irrigation canals along the longitudinal slope of the plains, it was common for early farmers to lead them down slope at right angles to the main levee-crest channels. In addition to saving Sumerian communities from digging extremely long canals, it incorporated a degree of flexibility into canal construction. As noted above, the higher gradients of levee slopes provide greater flexibility for the distribution of water to the fields and were less likely to silt up. Such short spur channels could therefore supply irrigation modules of modest scale, each serviced by a single canal of 2–5 km length. Each module was then capable of being organized by kin groups or small-scale communities (Fernea 1970; Pollock 1999, p. 31; Wilkinson 2013). This is in line with the conclusions of Rost, who for the Ur III period, questioned the prevailing model of highly centralized irrigation management to argue that only part of most irrigation works was organized by the state and that local populations (kin-groups and sections of tribes) participated in their maintenance to a significant degree (Rost 2011).

In other words, as illustrated on the map adapted from Adams (Fig. 10), very large-scale irrigation systems can develop incrementally as a result of niche-construction from initial longitudinal channels on levees, but which can be administered locally. Specifically, the levee slope model fits the pattern of niche construction in which an initial crevasse splay was transmogrified into a spur canal constructed down the levee slope, and was then extended as needs required. In other words, progressive modification of a preceding system laid the template for that which followed.

Sedimentation and the role of labour

Whether the growth of the hydraulic system was propelled by "natural" population increase, by food demands from cities in the region or by a combination of factors will be discussed below. However, if these original levee-break systems were to develop into larger-scale intensively farmed hydraulic landscapes, it would have been necessary for them to grow, presumably by means of some process of positive returns. In addition to the external demands for food production to supply the populations of the growing cities, which would encourage population growth in the food-producing irrigated areas, the demand for labour would also increase in order to service the growing network of canals, increased intensity of cropping as well as the burden of sediment removal.

Channels in southern Iraq, whether natural or artificial, accumulate sediments which are then incorporated into the alluvial zone by the aggrading surface of the river belt (which results in the growth in height of the levee). Therefore channels must be cleaned regularly to remove sediments, to ensure that water can flow smoothly, otherwise the channel would become choked and might flood. Today, the main Euphrates branches such as the Hindiya, the Hilla, the Shamiyah and the Kufa in the western parts of the plain have to be cleaned every 5 years whereas the minor irrigation canals have to be cleaned every year (IMWR 2002; Fig. 11). Moreover, the smaller irrigation canals in the agricultural fields have to be cleaned by farmers at least every planting season. In the case of the main branches, sand is the main cause of choking, but in minor irrigation canals this is caused by silt, sand and water plants; in field canals it is mainly from clay. For example, in the Haideri irrigation canal more than one meter of sediment is normally removed every year in order for water

Fig. 11 Canal located close to the Hilla branch in the western plains; this was dug around 1935 by hand shovels and shows how large amount of sediments accumulate alongside the canal (Jaafar Jotheri)

to reach the downstream fields (IMWR 2002). Today and in the recent past, the distribution of water among the irrigation canals and the Euphrates branches is under a high degree of government control and runs with a sophisticated system of dams, barrages and various discharges, so that government agencies are responsible for cleaning such channels. However, when Fernea conducted his studies in the area of Dagharah between 1956 and 1968, the role of tribal groups was also important. Consequently, although the Directorate of Irrigation had responsibility for the upkeep of the entire system, after water left the main government canal the responsibility for the construction and maintenance of canals rested with the cultivators (Fernea 1970, p. 123). In those parts of the irrigation system under tribal administration, each man is given a section of canal from which to dig out silt, with each individual being expected to clean a section of canal some 5 m long, 1 m wide and 50 cm in depth, with the cleaning lasting several days (Fernea 1970, p. 130). Moreover, if additional labour was required, it was brought in informally by means of *'awwana* ("helpers") who volunteer their labour freely under the condition that help will be returned when needed and that they are provided with food during the time they help out (Rost et al. 2011, p. 213; also Fernea 1970, pp. 130–132).

If the irrigation canals have not been cleaned in a given year their discharge will decrease and this leads to increased amounts of water in the main Euphrates branches, which may lead to flooding along them. This happened in the 1991 war when the Iraqi government neglected to clean many irrigation canals, and, as a consequence, the Hilla branch was nearly subjected to flooding in several locations. This was only prevented by the artificial raising of the natural levees to prevent the river from bursting its banks. There are several irrigation canals in Qaism city which gradually became abandoned because they were not cleaned for three consecutive years. It is now clear that regular cleaning and construction of barrages plays a vital role in keeping channels active, otherwise some will silt up and become abandoned while others will be flooded. In fact cleaning of channels becomes more difficult with time because of the accumulation of sediments year by year alongside the canal levees (Fig. 11), which necessitates two cleaning processes: one is removing sediments from the canal bottom and distributing them over the canal levees and the other involves removing these sediment to some distance from the levees to prevent it returning to the canal. However, when the cleaning process becomes particularly difficult, farmers prefer to dig another canal beside the old one because this is much easier than cleaning the abandoned one. A recent example of this occurred downstream of the Hilla branch in 1958 when two channels which had become silted up were replaced by two new canals alongside each other.

Indicative of the importance of sedimentation is that many Iraqi irrigation systems feature a pond which serves both to collect water when levels in the main rivers are low, as well as to decrease the sedimentation in the canals that were fed; they also operate as flood protection (Rost et al. 2011, p. 214). This highlights the complexity of the system: no one component serves a single function, which makes it difficult to quantify the role of any one feature.

The annual or biannual removal of sediments from the main channels and their canals and distributaries appears to have created a process of positive feedback. Increased work loads appear therefore to have contributed to the process of human niche construction by sucking in labour from elsewhere in order to service both the growing needs of intensive irrigated agriculture and the needs of canal cleaning. In other words, as the canal system is extended and canal gradients become progressively lower, within-channel sedimentation would increase. Cleaning activities and associated labour required are proportional to the amount of sedimentation, therefore as the gradient declines then more labour will be required to remove the sediments. Consequently for irrigation to accommodate the growing population of the developing cities, increasing amounts of labour were required in order to service both the highly intensive system of cropping (especially the date orchards and their lower storeys of horticultural plants) as well as the growing problem of sediment accumulation.

Whereas initial down-levee irrigation from the initial phase of spur canals (that is from levee gaps to fields) took advantage of the natural slopes and would have been relatively self-cleaning, as more lateral distributary channels were added at right angles from the spur canals, channel gradients would have been significantly decreased, with the result that sedimentation increased. This conforms to the increased frequency of cleaning noted above. Moreover, the fractal-like increase in length of irrigation channels combined with the associated decrease in gradients would, in theory, have resulted in a massive increase in total channel length, sedimentation rate and total sedimentation, all of which would have required much more labour, hence resulting in a process of positive feedback and need for increasing labour pools. Consequently, the role of sedimentation is not only of geoarchaeological interest but is also crucial to the social and economic development of irrigation.

Discussion: duration and sustainability of water systems

The central Mesopotamian channel system near Nippur therefore provides a good example of a herringbone pattern of short “spur” canals based upon a longitudinal levee. Its duration of some 3500–5500 years suggests that it formed a sustainable system of irrigation, which because most irrigation was conducted on the levee slopes or upper flood basins, would have been less liable to siltation, waterlogging or significant salinization (which tends to prevail in the lower basins: Altaweel 2013). Of significance for human niche

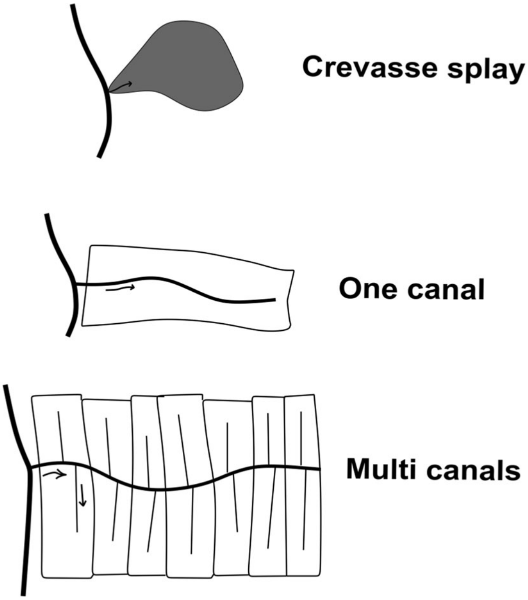

Fig. 12 Model of the development of spur canals from an initial phase of crevasse splay irrigation through to a herringbone pattern of irrigated fields

construction is that the plan form of the spur canals which even as late as the Sasanian period suggests a herringbone pattern, can plausibly be argued as having developed from an earlier phase of crevasse splays and simple spur canals as illustrated on Fig. 12.

With the help of human agency, the initial low-maintenance crevasse splay irrigated parcels developed into spur canals which required moderate levels of maintenance from small communities or lineages (Fig. 12a, b). With the additions of low gradient canals normal to the spur canals, the number of low gradient canals with gradients approximating those of the plain increased (Fig. 12c). Because these additional low-gradient canals accumulated silt and clay, they required more labour for maintenance and cleaning. Overall, the increased intensity of cropping (both multi-cropped palm gardens and levee slope cereal fields) together with the higher labour-requirement for maintenance required larger labour forces with the result that these increases led to positive returns in output as well as an upward spiral of labour demands. In other words, the simple niche construction system of crevasse splays gradually developed by processes of positive feedback into an intensively cultivated and densely populated hydraulic landscape.

The development of modular landscapes illustrated in Fig. 12a–c would have been accompanied by an increasing population density as more agricultural units were packed into the terrain (Fig. 12). As can be seen on Fig. 13, which is simply a model based upon estimated population densities from Fig. 12 and those supportable by the full Sumerian system, shows that by stage d, population densities significantly exceeded that of rain-fed Upper Mesopotamia (based on Wilkinson 1994). The final stage of this development, based upon the re-creation of a Sumerian system (Fig. 7), was associated with both the highest density of population as well as the most intensive labour regimes.

Although the cases presented do not necessarily represent chronological stages, the significant leap in population densities between cases b and c seems to represent the phase when positive feedback contributed to the growth of population. Increased positive feedbacks are indicated on Fig. 13 and are meant to illustrate, for example, when more inputs into the land result in the need for more labour, which, in turn, requires more fields to support those involved in the labour. This could also be illustrated by inputs of human

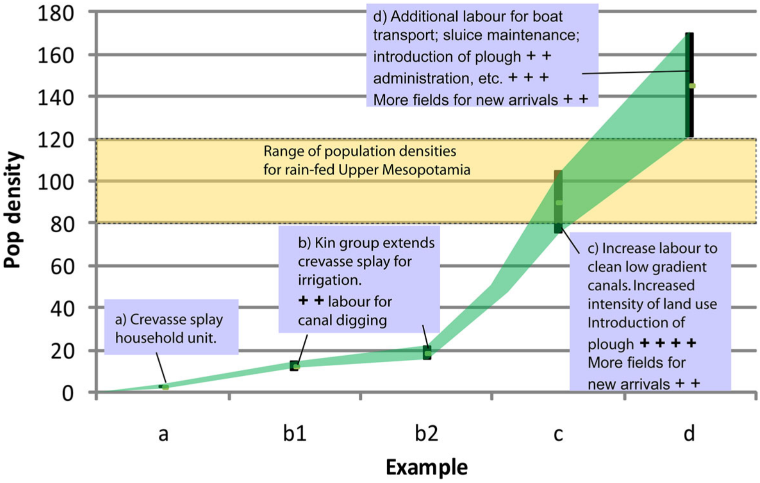

Fig. 13 Estimated population densities based on the examples illustrated in Fig. 12, and the herringbone (or trellised) Sumerian systems of Fig. 6

energy into irrigated systems which result in more than a doubling of inputs into irrigated than rain-fed systems (Netting 1993, p. 131). Similarly, the introduction of the plough (in the fourth or even fifth millennium BC in southern Mesopotamia: Postgate 1994, pp. 163–164) required both feed and pasture for the plough teams, but can increase agricultural production significantly (Netting 1993, p. 132). Overall, growth of the irrigation systems would result from both internal positive feedbacks, increased 'natural' population growth as well as external factors such as food demands from growing cities. Altogether, the irrigation systems discussed show the potential to be expanded and intensified, but also to be scaled down as necessary.

If such herringbone systems developed as a result of niche construction, they can be seen as equivalent to the small-scale "grass roots" social formations that are self-governing, collective-choice institutions for managing commonly-held resources (Mabry 1996, p. 22). Significantly, Mabry also argues that such hydraulic systems can endure political or economic collapses, although they are also vulnerable to being taken over by central governments (Mabry 1996, p. 19). This fits many irrigation systems in the Middle East, including that investigated by Kaptijn along the Jordan Valley (Kaptijn 2010; Ertsen 2010).

Although such small-scale systems apparently form a marked contrast to the large-scale imperial systems such as the Nahrawan canal (Adams 1965), it should be appreciated that because the central Mesopotamian levee-based canals are nested systems in which the small scale elements (i.e. the spur canals) form part of a much larger compound system (Fig. 10) they too can be regarded as large in scale. However, because they exhibit longevity and have the advantage of being sustainable over long periods they contrast with the large-scale imperial type systems which were often of relatively short duration (only several centuries) and very vulnerable to political and environmental events.

Some aspects of the development of the central Mesopotamian system resemble those of the Balinese systems investigated by Lansing and colleagues. For example, Lansing and Fox recognized a so-called "budding model" in which "irrigation works were created as a result of local initiatives, with new settlements budding off downstream as a result of population growth" (Lansing and Fox 2011, p. 928). In the Mesopotamian case, it can be suggested that there was an early phase of levee-crest date palm gardens nourished by the spring floods of the Tigris-Euphrates Rivers, followed by the extension down the levee slope of cereal fields. This aligns with the niche construction model of Bruce Smith in which "modification of vegetation communities is directed towards disrupting the reproductive rate of slowly growing "climax" vegetation, enhancing the short-term productivity of herbaceous plants, and increasing in-patch diversity" (Smith 2011, p. 838). In the Mesopotamian case cereal cultivation represented a plant resource with enhanced short-term productivity which then progressively spread down-levee as the canal or population (or both) grew.

Another key concept within Niche Construction Theory is that some organism-driven changes in environments persist as a legacy to modify selection on subsequent generations (O'Brien and Laland 2012, p. 436). Such "ecological inheritance" can be argued to depend on intergenerational persistence (often through repeated acts of construction) of whatever physical—or, in the case of humans, cultural—changes are caused by ancestral organisms in the local selective environments of their descendants (Odling-Smee 2010). Thus, ecological inheritance more closely resembles the inheritance of land or other property than it does the inheritance of genes (Shennan 2011). In the case of herringbone irrigation, the initial crevasse splay canals show topological persistence, so that the initial informal spur canals were subsequently formalised by generations of farmers who built upon the initial spur canals to pack in more canals to an increasingly dense and busy landscape.

Whereas the development and increased density of canals represent a consistent outcome of the evolution of irrigation systems, a secondary feature of such systems are the unintended consequences which can lead to future generations adapting to the changed circumstance produced by earlier generations. For example, the outflows of many Mesopotamian canals can lead to the development of marshes. Thus literary sources regard marsh formation as both a natural phenomenon and a cultural one (Eger 2011, p. 60) and near Borsippa between the eighth and sixth centuries BC, cuneiform texts mention that a large and permanent marsh had formed from the Hillah branch of the Euphrates, in this case hampering the construction of canals (Cole 1994, p. 87). Moreover, "the example from the Neo-Babylonian period shows how state-run infrastructure maintained a precarious and precious balance of canal irrigation systems and swamps as drainage and defense systems around urban communities—a balance that could be easily tipped with agricultural and irrigation intensification and several periods of severe precipitation and flooding." (Eger 2011, p. 60). As can be seen on Fig. 4, the spur canals of the herringbone systems debouch into flood basins which then accumulate water to become lakes and marshes. Rather than being seen as areas of waste however, such areas provided valuable resources to complement those provided by the irrigated areas: reeds, fish, waterfowl all occurred in abundance, and just as in the marshland communities of the Tigris-Euphrates deltaic region, the marshlands could readily become home to very specifically adapted human communities as described by Thesiger (1964). Although such marshes were in some cases the outcome of later irrigation systems, they in fact have a very long history extending well back into the earlier Holocene (Pournelle 2003), therefore their evolutionary history should be regarded as complex and not simply the outcome of human niche construction.

The early development of irrigation can also be argued to have contributed to genetic developments. Just as Laland and O'Brien argue for forest clearance leading to the spread of malaria in W Africa (2011), recent archaeological evidence from Tell Zeidan in northern Syria suggest that Schistosomiasis had already been contracted by the local populations by around 6000 BC (Anastasiou et al. 2014). Because Zeidan is located in an area that was too dry for rain-fed cultivation, the population probably relied upon some form of irrigation. Therefore the discovery of a schistosome egg in the pelvic area of one of 26 human skeletons excavated at the site argues that at this early date the local people were accustomed to wading in warm water, most likely irrigation ditches. In other words, even the very earliest phases of irrigation in Mesopotamia may have been associated with biological changes to the populations who must either have succumbed to diseases such as Malaria or Schistosomiasis, or adapted to them. The genetic developments associated with the creation of such niches therefore represent an important area for future research.

Conclusions

Because water management systems and canal patterns in southern Mesopotamia are profoundly complex, it would be overly simplistic to argue that the herringbone systems are omnipresent or even typical. Rather, they form an important feature of the hydraulic landscape, and they also satisfy many of the requirements for optimal irrigation: relatively good gradients, low degrees of siltation and management by relatively small lineages or tribal subdivisions. However, as is immediately apparent on satellite images and air photographs, many other patterns of irrigation occur. Such systems, which may include those of irrigated private estates, major governments schemes etc., if they violate the principles of levee slope irrigation, will suffer from the major challenges of siltation, overly long canals and other engineering problems.

Not discussed here, but of key importance to the development of Mesopotamian urbanism of all periods, is the increased role played by the channel networks. This was manifestly the case for the low sinuosity levee-based channels which formed an important part of the intercity transport system (Algaze 2008). These too formed part of a system of positive feedback which contributed to the growth of both cities and agriculture.

Human niche construction therefore supplies a valuable conceptual framework for understanding the development of ancient systems of water management. Because humans are seen as active agents in the creation and management of such systems, the explanations are not culturally or environmentally deterministic. As noted by O'Brien and Laland (2012, p. 448) environments are not fixed as rich or poor, rather they are dynamic and vulnerable to change as a result of the activity of niche constructors.

However, we must not lose sight of the long tradition that recognises that water management systems also represent a technology, and that technological studies have often dominated the study of ancient water systems. Therefore in his volume *The Nature of Technology* Brian Arthur states that: "the collective of technology build itself from itself with the agency of human inventors and developers much as a coral reef builds itself from the activities of small organisms" (Arthur 2009, p. 162). Consequently, it is not sufficient to see HNC as the "magic bullet" that explains the development of all water systems, rather it forms part of "the entangled (and constructed) human bank" that contributed to the "intergenerational transfer of ecological legacies" (Jablonka 2011, p. 784).

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