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The rivers of civilization

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A B S T R A C T

The hydromorphic regimes that underpinned Old World river-based civilizations are reviewed in light of recent research. Notable Holocene climatic changes varied from region to region, whilst the dynamics of floodplain environments were equally diverse, with river channel changes significantly affecting human settlement. There were longer-term trends in Holocene hydroclimate and multi-centennial length 'flood-rich' and 'flood-poor' episodes. These impacted on five identified flooding and settlement scenarios: (i) alluvial fans and aprons; (ii) laterally mobile rivers; (iii) rivers with well-developed levees and flood basins; (iv) river systems characterised by avulsions and floodouts; and (v) large river-fed wetlands. This gave a range of changes that were either more or less regular or *incremental* from year-to-year (and thus potentially manageable) or *catastrophic*. The latter might be sudden during a flood event or a few seasons (*acute*), or over longer periods extending over many decades or even centuries (*chronic*). The geomorphic and environmental impacts of these events on riparian societies were very often irreversible. Contrasts are made between allogenic and autogenic mechanism for imposing environmental stress on riverine communities and a distinction is made between channel avulsion and contraction responses. Floods, droughts and river channel changes can precondition as well as trigger environmental crises and societal collapse. The Nile system currently offers the best set of independently dated Holocene fluvial and archaeological records, and the contrasted effects of changing hydromorphological regimes on flood-water farming are examined. The persistence of civilizations depended essentially on the societies that maintained them, but they were also understandably resilient in some environments (Pharaonic Egypt in the Egyptian Nile), appear to have had more limited windows of opportunity in others (the Kerma Kingdom in the Nubian Nile), or required settlement mobility or exceptional engineering response (Huang He, Mesopotamia) to accommodate problems such as river avulsion, desiccation or local salinization.

1. Introduction

The first Old World civilizations, along the Huang He, Indus, Nile, Tigris and Euphrates rivers were almost entirely on alluvium. They were 'hydraulic' (cf. Wittfogel, 1957) or 'potamic' in the sense that they were in relatively dry environments and farming depended on natural inundation or controlled irrigation from river water. This most commonly involved floodwaters from 'exotic' rivers passing into semi-arid or arid environments; discharges were strongly seasonal, and in most cases derived from headwater precipitation regimes often very different to their receiving floodplains. Floods also brought nutrient-rich sediments. This provided the potential for a prosperous agriculture and for organised societies to develop urban cultures in which deified rulers, writing, and artistic creativity flourished. At the same time, these early civilizations were vulnerable to both political and environmental stresses, and there has been much debate as to which factors were most significant in contributing to periods of decline and collapse (McAnany and Yoffee, 2010; Butzer, 2012). From the environmental point of view, causes of settlement abandonment are believed to have included prolonged drought (e.g. the Indus; Giosan et al., 2012), channel network contraction and retraction through abrupt reductions in river flow (e.g. Nile in Nubia; Macklin et al., 2013b) destructive floods associated with short-term climate change (e.g. Huang He; Kidder et al., 2012), and long-term soil

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deterioration through salinization (e.g. Euphrates; Jacobsen and Adams, 1958). Flood regimes were essential to all Old World river civilizations but floods needed to be neither too large, nor too small or infrequent.

This paper considers the variability of river regimes: climate, hydrology and geomorphology driven, and collectively termed 'hydromorphic regimes'. These varied both spatially and temporally, and they underpinned the major hydraulic civilizations of the Old World. This is not at all to claim that environmental character and variability were necessarily of overriding importance, nor to minimize social and political factors for the development or the demise of ancient civilizations. Instead we explore with greater focus the opportunities and stresses which living in particular river environment posed. These were not uniform either in space or time, and we believe it important to provide evaluations of the diverse and dynamic qualities of these environments that are, as far as possible, independent of the evidence of human occupation. Were there characteristics of some alluvial settings which made them especially attractive or, ultimately, hazardous? If there were cultural crises, did they coincide with dated flood or drought episodes? Did civilizations or cities decline when particular river channels can be shown to have shifted course or dried up? Such changes need to be independently verified and precisely dated rather than hypothesised on the basis of settlement abandonment, and they need to be understood in the properly combined context of regional and local palaeohydrology, as well as river channel and floodplain dynamics.

What has been confirmed in recent years, both from much improved records of Holocene climate variability (Mayewski et al., 2004; Wanner et al., 2011), and from directly studying the alluvial sedimentary record (Macklin et al., 2012b), is that the Holocene was characterised by significant changes in river discharge regime. In a growing number of environments, episodes of higher and lower flood frequencies and magnitudes have been demonstrated (Ely et al., 1993; Knox, 1993; Macklin et al., 2002, 2005, 2006, 2010, 2012a; Macklin and Lewin, 2003, 2008; Thorndycraft and Benito, 2006; Zielhofer and Faust, 2008; Sinha and Sarka, 2009). This is of special significance for presently semi-arid and arid environments (Waters, 2000; Huckleberry and Duff, 2008; Harden et al., 2010; Macklin et al., 2013b) where quite small differences in annual flood level or runs of drier years are likely to have had a considerable impact on community prosperity and on the durability of physical structures and the organisation of water distribution. Awareness of such sensitivities in past times is tangentially confirmed, for example, by the efforts made to gauge flood levels in Egyptian 'nilometers' and the use of such information to set levels of taxation (Bell, 1970; Butzer, 1976). Crop yields, and therefore equitable tax demands, could be related to floodwater levels.

A further important consideration is that large rivers and their floodplains – such as the Huang He, Indus, Nile, Tigris and Euphrates – are, like large rivers in general, highly varied both in dynamics and form (Lewin and Ashworth, 2014a, 2014b). In some, river channels are relatively stable for centuries; they may aggrade their beds and bank zones, and then avulse to a new location (Huang He, lower Euphrates) – but only rarely. Where rivers flow through broad basins, such avulsions can shift channels in single events for tens to hundreds of kilometres. Channel contraction and wholesale abandonment of once multiple channels took place along the Nubian Nile (Woodward et al., 2001; Macklin et al., 2013b) and retraction in former tributaries of the Indus (Giosan et al., 2012). In other situations channels have shifted short distances but frequently, with annually evolving bank erosion and meander loops (upper Tigris), or the formation of islands which over decades to centuries have become attached to floodplains (the Nile in Upper Egypt). In yet others, highly unstable braided systems occupy a broad zone of ephemeral channels and temporary gravel or sand bars (middle Indus). Changes here may sweep across entire floodplains or alter the local topography in a matter of one or two seasons. Finally, river incision, largely resulting from a changed balance between sediment supply and runoff, may considerably affect groundwater levels and floodplain agriculture as channels become entrenched. However, on the large rivers here being considered, channel entrenchment has not played a major role in settlement development as it did for example in the American Southwest (e.g. Hack, 1942; Waters and Field, 1986) and mountain piedmont settlements along the Pamir and Tien Shan mountains, Central Asia (Lewis, 1966; Macklin et al., in review).

Despite individual exceptional studies (e.g. Hack, 1942; Adams and Nissen, 1972; Butzer, 1976; Waters and Field, 1986; Wilkinson, 2003; Morozova, 2005; Arnaud-Fassetta et al., 2010; Giosan et al., 2012; Macklin et al., 2013b), there has been limited overall appreciation of the global complexities of floodplain hydromorphologies that formed the environmental contexts for early riverine agriculturalists. Considering these issues only for broad geographical areas, or from the viewpoint of cultures and governance alone, does not provide an adequate framework for understanding the site opportunities and hazards that these populations faced when their life ways depended entirely on local river dynamics and flooding regime. Large rivers such as the Egyptian and Nubian Nile, the Tigris, the Euphrates, the Indus and the Hwang He, both at present and during the periods that these first Old World civilizations flourished, were dissimilar from each other, and they also displayed considerable variability from reach-to-reach. Hydroclimatic fluctuations, or major floods and droughts, which might have been catastrophic in one situation, could be survived in another – because of differences in natural river channel dynamics, floodplain morphologies and floodwater distribution systems. It is also likely that some changes that were ruinous from a settlement point of view, such as channel shifts and avulsions, were triggered by relatively minor events within the normal spectrum of local hydrological regimes and not necessarily related to external climatic signals. For human exploitation given the technologies available, *local* site opportunities were of particular importance. These may have been almost incidental to the main activities of rivers, as in the provision of ponded 'reservoirs' of annually replenished water in cutoff palaeochannels or in geomorphologically moribund river branches that still carried flow, at least seasonally. The ways floodwaters spread, could be 'stored' on floodplains, or could be re-directed must also have been crucial. In the context of prehistoric and early historical irrigation-based agriculturists, it is necessary to consider what may now seem to be quite minor features of alluvial landscapes as these often had a major controlling impact on the routing of floods and of water storage.

There have been considerable advances in river system and environmental change research in the last several decades that have particular relevance to the study of riverine civilizations. These have involved: a greater understanding of alluvial sedimentology (Miall, 1996; Brown, 1997; Marriott and Alexander, 1999; Bridge, 2003); an appreciation of the global variety to floodplain character and evolution (Nanson and Croke, 1992; Schumm and Winkley, 1994; Tooth, 2000, 2013; Latrubesse et al., 2005; Gupta, 2007; Tooth and McCarthy, 2007; Latrubesse, 2008; Weissman et al., 2010; Ashworth and Lewin, 2012; Lewin and Ashworth, 2014a, 2014b); the availability of high-resolution maps of floodplains and channel ways generated by LiDAR (Lane, 2006; Jones et al., 2007; Wheaton et al., 2010) and other remote sensing imagery (Syvitski et al., 2012); the sequencing of floodwater inundation and transmission (Anderson et al., 1996; Mertes, 1997; Schumann et al., 2009; Trigg et al., 2012); and the numerical modelling of catchment and river system responses to autogenic (Nicholas and Quine, 2007; Nicholas, 2013) and allogenic (Van De Wiel et al., 2011) change. The wider availability and application of ^{14}C and luminescence dating in riverine contexts have also greatly increased the precision with which environmental changes can be identified in the fluvial archive (Macklin et al., 2002; Macklin and Lewin, 2008; Williams et al., 2010; Macklin et al., 2012b, 2013a; Benito et al., 2014). Clear archaeological benefits from using such approaches have been demonstrated for some time in the American Southwest, where investigations have been coupled with process-based analysis of dynamic fluvial environments, underpinned by robust geochronologies (Waters and Field, 1986; Huckleberry, 1995; Waters, 2000; Clevis et al., 2006; Huckleberry et al., 2013). Similar geomorphological advances are now being made in the Nubian (Woodward et al., 2001; Williams et al., 2010; Macklin et al., 2013b) and Egyptian Nile (Bunbury et al., 2008; Ghilardi and Boraik, 2011; Marriner et al., 2012; Butzer et al., 2013), in the Indus valley (Giosan et al., 2012), and in the Huang He (Yellow River) region of China (Kidder et al., 2012).

Taking the 'long view' of river channel and floodplain environments that fluctuated over timescales of decades to thousands of years is appropriate when examining the sustainability of civilizations that are known to have lasted for equivalent time periods. Some initial caveats in the approach we have adopted should also be acknowledged. First, as well as assessing those alluvial environments which did form the basis for agriculture and urban-based societies, we also note that others were not so suited, but did support prosperous and settled fishing and hunting communities (e.g. Pacific Northwest of North America; Campbell and Butler, 2010). Secondly, where possible, we set riverine environments within the context of Holocene climatic fluctuations as now known (Mayewski et al., 2004; Wanner et al., 2011), and this has required careful selection and analysis of hydroclimatic records. Thirdly, the river systems examined are also now different from ancient times (Tockner and Stanford, 2002; Vörösmarty et al., 2003; Nilsson et al., 2005; Syvitski et al., 2005): flows are regulated by dams and modern irrigation schemes, channels have shifted over a period of several millennia, and many valley floors have accumulated several metres of sediment obscuring the nature of former floodplains and river channel systems (Wilkinson, 2003; Arnaud-Fassetta et al., 2010; Ghilardi and Boraik, 2011; Chen et al., 2012; Kidder et al., 2012).

This paper is divided into five sections. In the first, we outline a hydroclimatic framework for Old World river civilizations. This is then followed by a review of floodplain morphologies and floodwater dynamics that had an influence of floodwater farming, irrigation and ancient river civilization settlement. Human-river environment interactions are then considered for the Nile Valley, including the impact of longer-term climatic shifts as well as the periods of abrupt climate change that occurred over timescales that would have been perceptible to communities. Finally, the special nature and distinctive environmental trajectories of 'rivers of civilization' are highlighted and pointers are given to potentially productive lines of future research needed to further support an understanding of human dynamics in the watery realm.

2. Holocene hydroclimates and hydrological regimes of Old World river civilizations

In terms of global climate systems and their influence on river regime, Old World river civilizations can be sub-divided into the monsoon-controlled Huang He, Indus and Nile rivers, and the mid-latitude Euphrates and Tigris rivers whose catchment and headwater hydrology are controlled by westerlies that propagate cyclones generated in either the Atlantic or eastern Mediterranean. Monsoon-influenced rivers have a 3–4 month long summer season flood followed by much reduced flow, evidenced most notably the Indus and Nile rivers (Fig. 1A, B). The Mesopotamian Euphrates and Tigris rivers have prominent springtime nival and rain-fed floods (Fig. 1D, E). The yearly *variability* of monthly flow is significant on the Indus (1a, f) and Huang He (Fig. 1C, F) but less on the Nile and Tigris (Fig. 1B, F), but the annual *timings* of peak flows of the Euphrates (Fig. 1E), Tigris (Fig. 1D) and especially the Huang He (Fig. 1C) are also irregular.

Over millennial timescales during the Holocene, the redistribution of solar energy due to orbital forcing was the cause of a progressive southwards shift in the Northern Hemisphere (NH) summer position of the Inter-tropical Convergence Zone (ITCZ). This was accompanied by the gradual weakening of the monsoon system in Africa and Asia, and increasing dryness or desertification of the Huang He, Indus and Nile catchments. On a multi-centennial timescale, Holocene climate was also variable, fluctuating between generally warm and wet, and cold and dry states. This is perhaps best represented in the North Atlantic region where Holocene climate has been characterised by a series of shifts in ocean surface hydrography during which drift ice and cooler waters in the Labrador and Nordic Seas were repeatedly advected southward and eastward. Nine of these so called 'Bond events' have been detected in the Holocene, the most recent being the Little Ice Age (LIA), with a postulated existence of a cycle with an average length of approximately 1470 ± 500 years (Bond et al., 2001). North Atlantic ice-rafting events have been shown to correlate with most of the weak periods of the Asian Monsoon over the last 9000 years (Wang et al., 2005). Wanner et al. (2011), based on carefully selected 10,000-year-long time series of temperature and humidity/precipitation, as well as reconstruction of glacial advances during this period, identified 6 cold events at 8300–8100, 6400–6200, 4800–4600, 2800–2600, 1650–1450 and 650–450 cal. BP. However, a clear cyclicity was not found and the spatial–temporal variability of temperature and humidity/precipitation during these events was very high. A large number of dry anomalies occurred during the earliest cold events at 8300–8100 and 6400–6200 cal. BP, as well as during the Dark Age cooling at 1650–1450 cal. BP. Conversely, an average (4800–4600 and 650–450 cal. BP) and very low number of dry anomalies (2800–2600 cal. BP) was registered during the other 3 periods, including the LIA. Most likely processes such as meltwater flux into the North Atlantic, low solar insolation, in combination with a slowdown of the thermohaline circulation, and in some cases a series of volcanic tropical eruption, played major roles in the timing and duration of these cold events (Wanner et al., 2011).

Changes in the dominant modes of climatic variability in the North Atlantic and Pacific also contribute to climate change over centennial to multi-decadal timescales (Wanner et al., 2011).

The associated cooling of the NH, combined with changing temperature gradients in the world's oceans, led to increasing ENSO (El Niño–Southern Oscillation) amplitude and, possibly, increasing negative NAO (North Atlantic Oscillation) indices up to the beginning of the last millennium (Wanner et al., 2011). ENSO and NAO are the major high-frequency modes to influence flooding and drought episodes in the African and Asian rivers considered in this review.

3. Floodplain morphologies

It was the materials that rivers carried, as well as the water they delivered, that determined river potential for long-term civilized societies. Of course water availability was crucial but whether a sustaining environment could exist for urban and agricultural communities for centuries to millennia requires also consideration of geomorphology and longer-term sediment dynamics. Nutrient input, the build up of fine sediment, the delivery of saline waters,

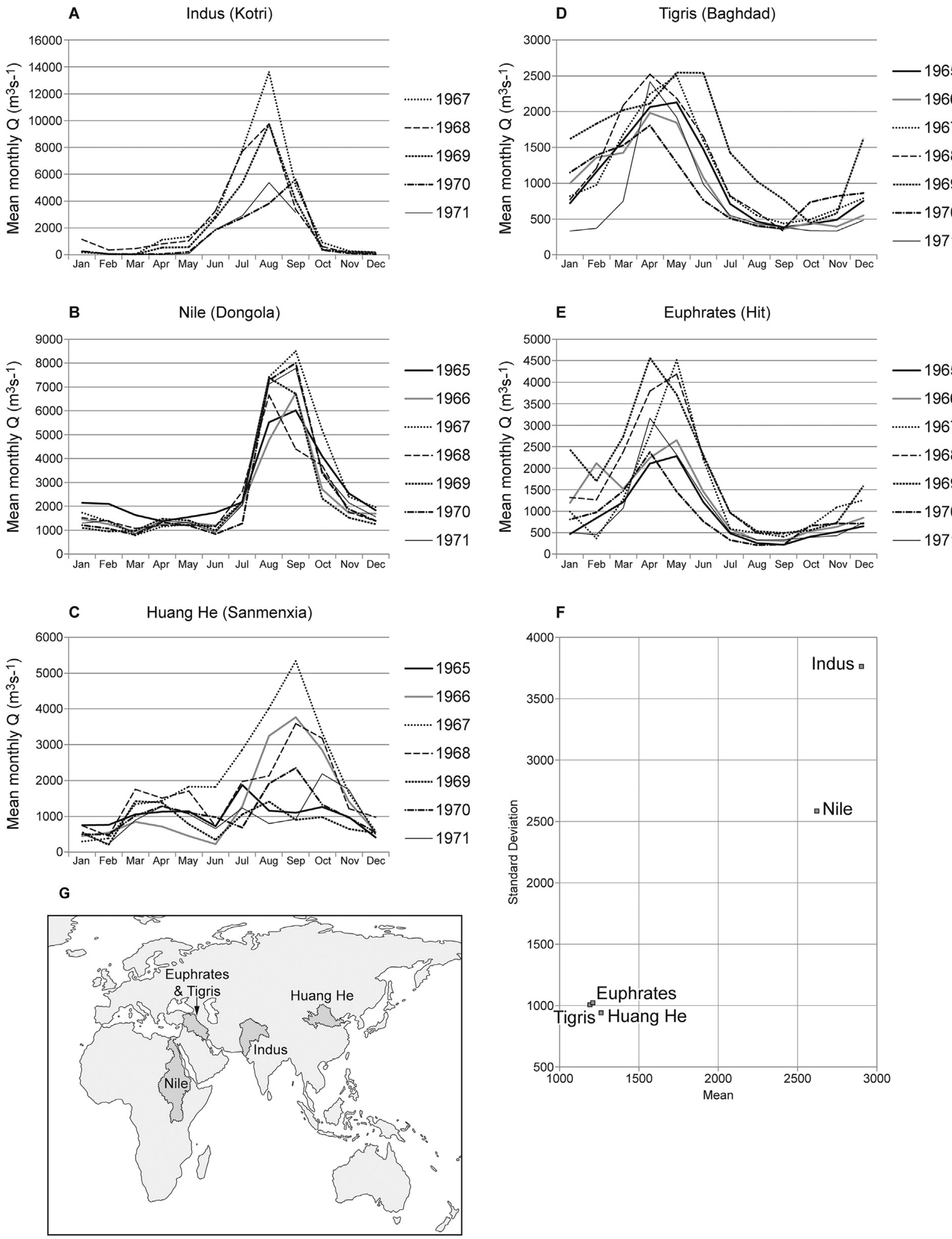


Fig. 1. Mean monthly river flows for the Indus (A), Nile (B), Huang He (C), Tigris (D) and Euphrates (E) catchments; (F) plot of mean monthly flow versus standard deviation of mean monthly flow for Tigris, Euphrates, Huang He, Nile and Indus catchments; and (G) location of Tigris, Euphrates, Huang He, Nile and Indus catchments.

the formation (or otherwise) of natural levees, the stability of shifting channels including rare avulsions, network expansions and contractions – all these greatly determined how suitable a floodplain environment was for settlement and farming from one generation to the next. Different river channel patterns (meandering, braiding and anastomosing) characteristically have different combinations of meso-scale morphological elements (Fig. 2); these generally change in character down-river and play a

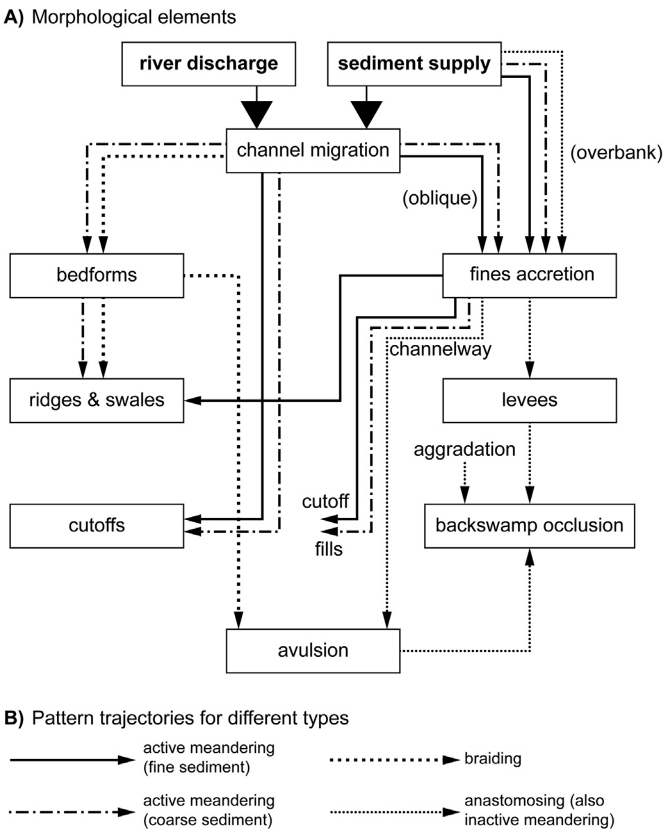


Fig. 2. Morphological elements and development trajectories for different types of river channel patterns.

significant role in determining the spread of inundation and the location of settlements.

Table 1 presents an array of alluvial river channel and floodplain elements likely to be of crucial practical importance for the potential development of settlement sites and irrigation-based agriculture. The cited literature demonstrates the range of forms, flows and changes that can occur. Although major civilizations were, broadly speaking, based on aggrading alluvial environments in drier climates, their floodplain morphologies were differentiated according to flows and the sediments transported and deposited on-site. Fig. 2 shows that this usually involves *form associations* constructed from fine or coarse sediments (with fine sediments generally to the right of the diagram, though sandy bedforms are also characteristic of some environments). Active channel migration involves one set of associated landforms (ridges and swales, cutoffs) whilst sedimentation in and alongside stable aggrading channels leads to another (levees with back swamps). As a result, different flooding and settlement scenarios may be envisaged (Fig. 3):

(a) *Alluvial fans and aprons* may build up along fringing mountains; they may have shifting, incising and relatively steep gradient radial channels. Discharges may decrease downstream away from precipitation and runoff sources, though they may sustain groundwater levels for considerable distances. These may be tapped by wells or directed in subsurface channels, such as the Qanats of Iran. Any out-of-channel flows are oriented downslope and at an acute angle to active river channel alignment. Episodic reorganisation of channels *without* climatic change is also normal to fan evolution (Nicholas et al., 2009), and this also affects water availability at particular places. These environments are sensitive both to variations in mountain precipitation regimes, the balance between sediment supply and water discharge, and to episodes of incision when relative rates of sediment input are in decline. Thus many fans have single channel belts that have entrenched during the Holocene when sediment supply has generally been less than under Pleistocene conditions. The Holocene has broadly been marked by greater fan stability, but with further episodes of erosion and infilling producing terracing within entrenched valleys as Holocene climates themselves have varied

Table 1
River channel and floodplain characteristics: practical considerations for floodwater agriculturists.

	Selected studies
The channel	
1. Channel pattern	
(single/multiple, straight/sinuous, stable/actively-mobile, anastomosis, braiding, meandering)	Leopold and Wolman, 1957; Ferguson, 1987; Nanson and Croke, 1992; Nanson and Knighton, 1996; Latrubesse, 2008; Wheaton et al., 2010; Ashworth and Lewin, 2012; Lewin and Ashworth, 2014a.
2. Dimensions & bedforms	
(widths & depths, bar dimensions & shift pattern)	Williams, 1978; Ferguson, 1986; Miall, 1996; Bridge, 2003.
3. Channel banks	
(height & variation with river stage, slackwater margins, levees & their dimensions, breaches & crevasses)	Adams et al., 2004; Slingerland and Smith, 2004.
4. Change activity	
(lateral migration, avulsion and abandonment, vertical incision or aggradation)	Petts et al., 1989; Howard, 1996; Thorne et al., 1997; Brown, 1997; Macklin et al., 2013b. Lewin and Ashworth, 2014a.
The floodplain	
1. Dimensions	
(width, gradients, character of valley-floor margins)	Wolman and Leopold, 1957; Lewin, 1992; Ashworth and Lewin, 2012.
2. The surface	
(tabular, convex, diversification by former channels)	Lewin, 1992; Graf, 1988; Lewin and Ashworth, 2014a, Gurnell and Petts, 2002; Lane, 2006.
3. Water distribution	
(flood-out channels, lakes, wetlands, seasonal inundation sequences & extent)	Butzer, 1976; Mertes, 1997; Tooth, 1999; Paira and Drago, 2007; Tockner et al., 2009; Lewin and Ashworth, 2014b.
4. Change activity	
(sediment accretion, work-over rate by channel erosion, cutoff infilling, flood channel changes)	Tooth, 2000; Maddy et al., 2001; Jones et al., 2010; Howard, 1996; Lane, 2006.

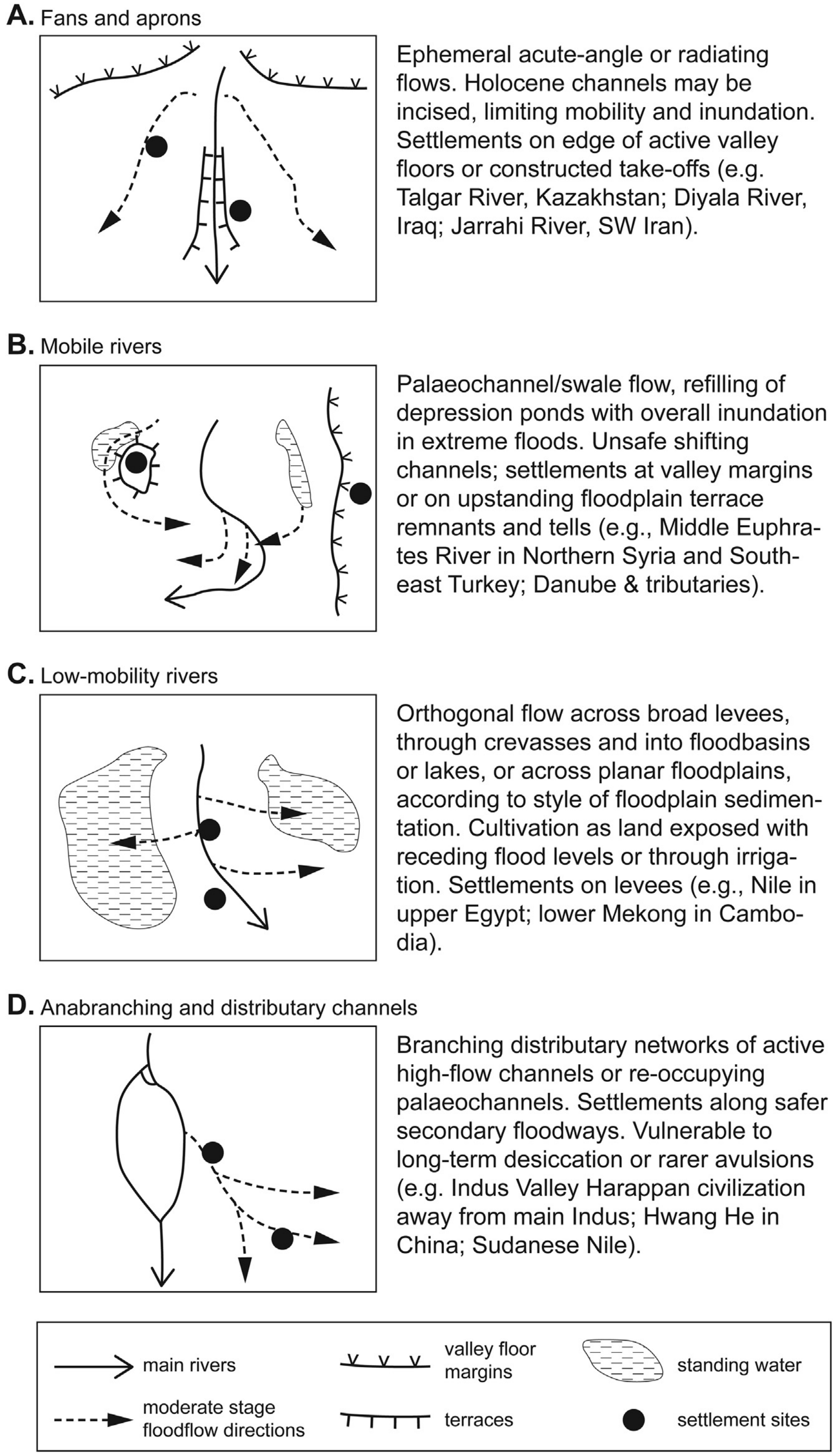
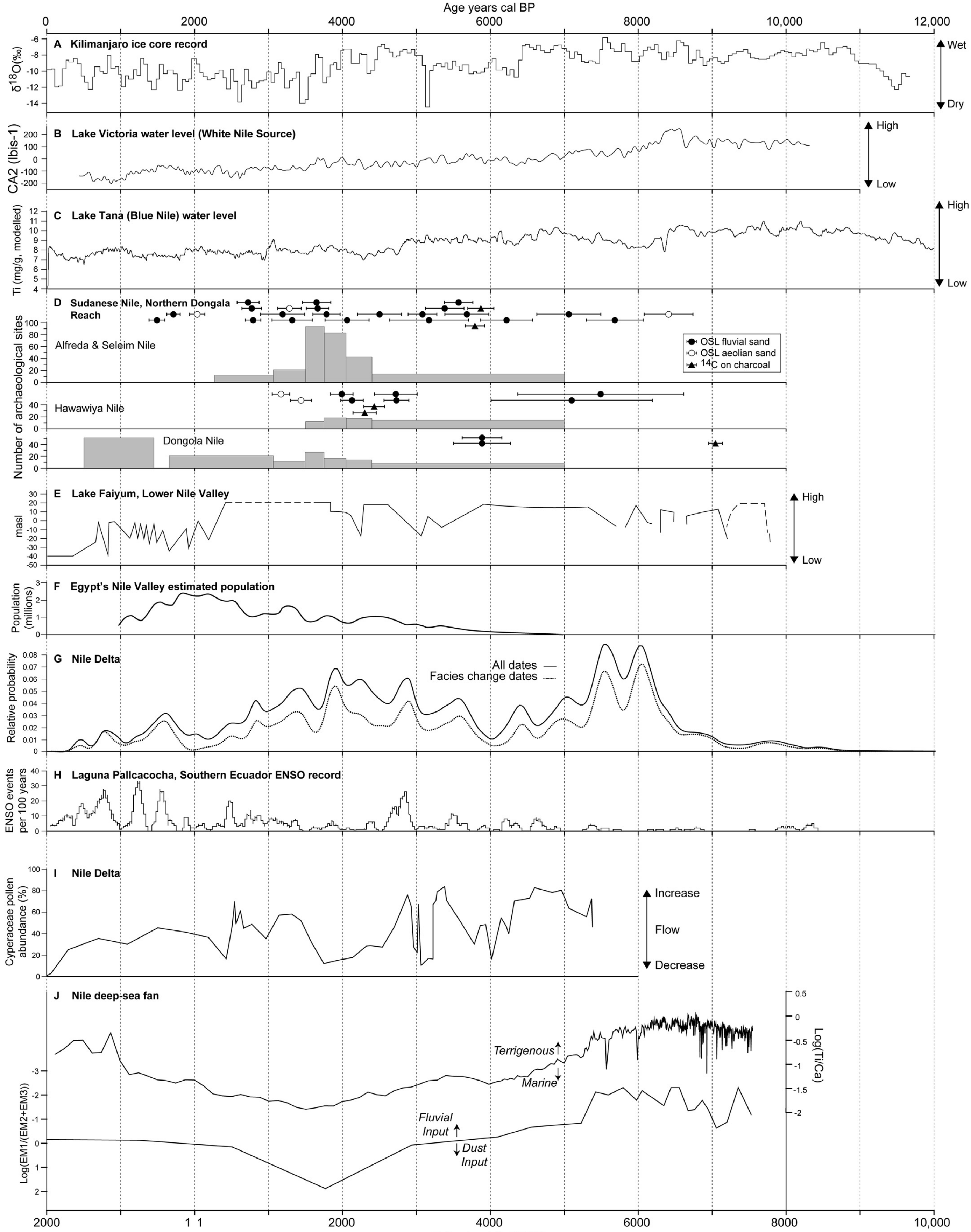


Fig. 3. Flooding styles for (A) alluvial fans and aprons, (B) mobile rivers, (C) low-mobility rivers, and (D) anabranching and distributary channels.

(Macklin et al., in review). In low angle fans, such as those described by Walstra et al. (2011) in southwest Iran, human intervention is a very important factor in their development through the use of levee breaks as locations for inlets to irrigate canals and the transformation of crevasse splays into rapidly prograding irrigation lobes.

(b) *Mobile rivers* with braided or actively meandering channels may produce laterally shifting rivers and tabular floodplains with relief provided by cutoffs, and accretionary ridges and swales. This is characteristic of higher-energy ‘proximal’ river environments at moderate gradients near the sources of both water and sediment. These may be less suitable for riverside settlements that would be liable to repeated destruction; the plain itself may be cultivable after seasonal inundation, but valley-margin building sites, or terraces where there has been river incision, may be preferable. Mobile river channels


Age years cal BP
A Kilimanjaro ice core record
δ18O(‰)
Wet
Dry
B Lake Victoria water level (White Nile Source)
CA2 (lbis-1)
High
Low
C Lake Tana (Blue Nile) water level
Ti (mg/g, modelled)
D Sudanese Nile, Northern Dongala Reach
Alfreda & Seleim Nile
Hawawiya Nile
Dongola Nile
Number of archaeological sites
OSL fluvial sand
OSL aeolian sand
14C on charcoal
E Lake Faiyum, Lower Nile Valley
masl
F Egypt's Nile Valley estimated population
Population (millions)
G Nile Delta
All dates
Facies change dates
Relative probability
H Laguna Pallcacocha, Southern Ecuador ENSO record
ENSO events per 100 years
I Nile Delta
Cyperaceae pollen abundance (%)
Increase
Flow
Decrease
J Nile deep-sea fan
Terrigenous
Marine
Fluvial Input
Dust Input
Log(EM1/(EM2+EM3))
Log(Ti/Ca)
Calendar date AD/BC

with shifting bars may not be suitable for large-scale water transport, but cutoff channels may form small-scale wetland and persistently available surface water resources that for early populations may have been as useful as the rivers themselves. These alluvial environments are sensitive to changes in water and sediment supply rates which produce episodes of floodplain incision or aggradation. The upper and middle reaches of the Euphrates (located in present-day Turkey and Syria) and Tigris rivers (present-day Iraq) are typical in this respect with settlements located on Late Pleistocene or early Holocene age river terraces (Kuzucuoglu et al., 2004). Further downstream in northern Syria, tell sites (now flooded by the construction of the Tishrin Dam) are located about 10 m above the modern floodplain. Oguchi and Oguchi (1998) report flood sediments within tell deposits, indicative of periodic large floods in the Ubaidian period c. 8450–5750 cal. BP.

(c) *Low mobility* perennial rivers and a dominance of fine-grained (clay, silt and sand) sediment, may develop levees fringed by seasonally inundated floodplains. Fixed-location levees may form relatively dry and secure settlement sites (e.g., Nile in Upper Egypt, Butzer, 1976). Formed by advecting sediment during floods, these have back slopes and sometimes crevasses and sediment splays orthogonal to channels. This is characteristic of 'distal' and largely aggrading environments at low gradients that are remote from sediment-supply sources (possibly by hundreds of kilometres). However, levee settlements are hazardous places during the most extreme flood events. Channel-breaching by artificial means, both to extend watered areas to lower flood levels on the levees themselves were common water management practices.

(d) *Anabranching and distributary channels* fanning out across broad alluvial megafan surfaces, or across tectonic depressions, may also be found on a large scale, as in the Indus and other valleys bordering the Himalayas as well as in the Huang He River as it leaves a series of narrow gorges and spreads across the northern China coastal plain. Where plainland channels emerge from mountain fringe apex points, one or more may be active at any one time with avulsion leading to channel relocation by tens or even hundreds of kilometres in down-channel locations (Heyvaert and Baeteman, 2008; Kidder et al., 2012). Distributary networks may also contract during periods of reduced runoff, and riverside settlements may consequently suffer from deprivation of their water supply. A distinction may be made between *flow contraction*, meaning narrowing of a channel, and *flow retraction*, meaning a shortening of the distance to which flowing waters extend. Whether because of avulsive channel relocation or climate-related flow reduction, settlements adjoining watercourses may need to shift unless their economy is to decline. Both flow contraction and retraction may happen simultaneously. Early societies, such as the Indus Valley Civilization (Giosan et al., 2012) also used ephemeral flood-out channels for floodwater farming as well as perennial main rivers and their riparian floodplains. These flood flows and groundwater feeds were more manageable than those of large rivers, but may have varied in water delivery from year-to-year. Some also depended also on upstream tapping points within alluvial areas that were liable to change. These environments are notably sensitive to allogenic changes that alter the flow regimes upon which settlements depend.

(e) *Permanently water-filled floodbasins* within broad (tectonic) trough-shaped valleys and wider depressions characterised by low sediment supply were another favoured location for settlement. Freshwater lacustrine deltas may extend to provide cultivable land, with seasonally available land also in the zones between high- and low-lake levels. In some situations and with regionally organized effort, these may be further drained for agriculture. In others such as the Tonle Sap (Great Lake) area of present-day Cambodia in the lower Mekong basin, so called 'receding flood' agriculture was, and is, practiced (Arias et al., 2012). Topographic gradients in these environments may be subtle, so that reticulate drainage and irrigation systems are dominated by planned layout design (e.g. Angkor in Cambodia; Fletcher et al., 2008). Wetlands and lakes may also be important food sources although standing water may be significant in disease vector terms; drainage may be possible but even this may leave near-stagnant water bodies that foster disease transmission (Smith et al., 2013).

Morphological changes in each of these environmental settings (Heyvaert and Baeteman, 2008) may be described as regular or *incremental* if they occurred frequently (e.g. river bank erosion), and would thus easily have been appreciated by early inhabitants, or *catastrophic* if their occurrence was rare and probably quite unexpected (e.g. channel avulsion or channels drying up). Avulsions occur in several situations: on fans, where radial streams periodically relocate laterally; along braided or meandering floodplain channels; on large-scale and low gradient megafans; and in deltaic environments where individual channels may silt up (Törnqvist and Bridge, 2002; Slingerland and Smith, 2004; Morozova, 2005; Heyvaert et al., 2011). These may be triggered by exceptional floods overtopping levees but also by quite moderate events as well; this may require a long 'preparatory' period of local channel aggradation, and it is only after this that channel shifts occurs. Others may relate to channel re-alignment and the exploitation of pre-existing floodplain depressions (Morozova and Smith, 2000; Ashworth and Lewin, 2012). In all such circumstances, a simple association with extreme hydroclimatic events may not always be justified. Dry period hazards may, however, be very sensitivity related to external hydroclimatic variations, including channel contractions over large parts of floodplain systems. This includes retraction of distributary networks, diminution of channel sizes and restriction of flood extent (cf. Macklin et al., 2013b).

To the suite of these opportunities, and threats, that differences in floodplain morphology offer to the establishment of long-term riverine civilizations should be added the negative factor of salinization in dryland environments. This may be exacerbated in areas with unfavourable river solute loadings (controlled by upstream

Fig. 4. Holocene hydroclimatic records of the Nile Catchment, Valley and Delta. (A) Kilimanjaro ice core record (Thompson et al., 2002) close to the White Nile headwaters; (B) Lake Victoria (Stager et al., 2003) water level record (White Nile source); (C) Lake Tana (Marshall et al., 2011) water level record (Blue Nile source); (D) Integration of archaeological data with dated phases of fluvial and aeolian sand deposition in the Northern Dongola Reach and regional palaeoclimate records (OSL—optically stimulated luminescence). Bars show number of archaeological sites recorded for each channel system for each period (Macklin et al., 2013b); (E) Lake Faiyum (Hassan et al., 2012) water level; (F) Egypt's Nile Valley estimated population (Butzer, 1976); (G) Summed probability density function plots for radiocarbon dates from the Nile delta's Holocene record. The plot is divided into total dates and facies change dates for the period 12,000 cal. years BP to present. The y-axis is probability per year and the x-axis corresponds to the calibrated radiocarbon years BP (Marriner et al., 2012); (H) Laguna Pallcacocha, southern Ecuador ENSO record (Moy et al., 2002) showing the number of ENSO events per 100 years; (I) river flow at the Nile delta (Bernhardt et al., 2012); and (J) Time variations of elemental content in Nile deep-sea fan Holocene sediments (Blanchet et al., 2013). Ti/Ca ratio is a tracer for marine versus terrigenous sedimentation. EM1/(EM2 + EM3) ratio provides a reconstruction of the fluvial/aeolian contribution to the terrigenous fraction.

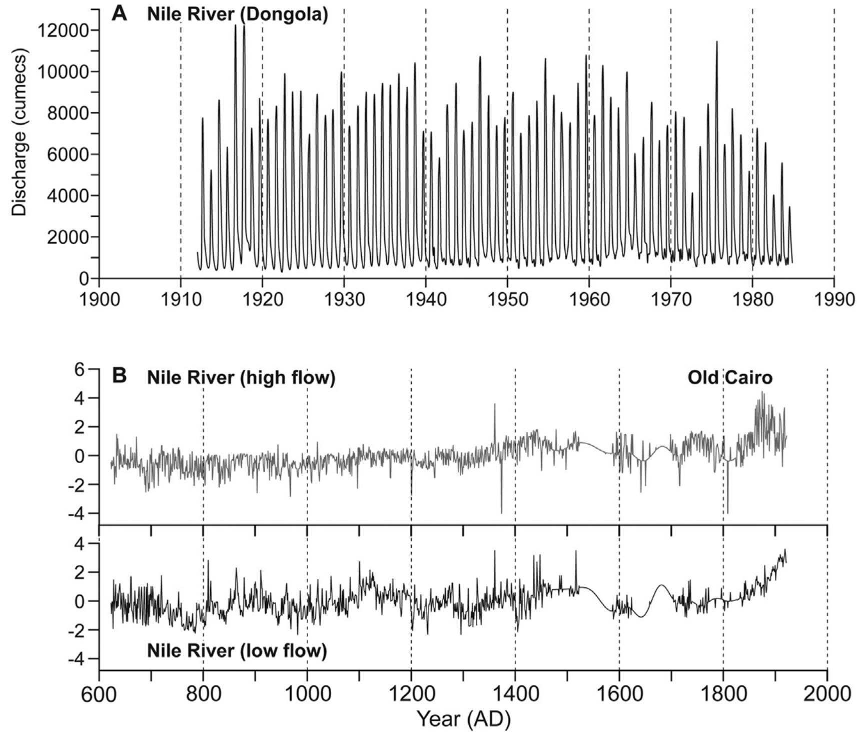


Fig. 5. (A) Instrumental Nile River flow records at Dongola (Conway, 2000); and (B) Nile river annual high- and low-flow records from the Rodah Island nilometer AD 622–1922 (Kondrashov et al., 2005).

catchment geology), and where water levels remain at or near the surface such that capillary rise and evaporation lead to surface salt precipitation, as in many drained and irrigated wetlands. Salinization may depend on 'natural' river flow and sedimentation dynamics, but more usually on irrigation practice. Over the longer term, human activities may modify local hydrology in other ways – by diverting flows leading to channel change and shrinkage, by bank protection and channel stabilization, by inadvertently increasing the vulnerability of urban areas as they expand into topographically unsuitable situations, and by sedimentation in low-gradient engineered channels. For such reasons, initially satisfactory water exploitation may translate into longer-term vulnerability of settlements and agriculture from increased flood risk or soil salinization. This is perhaps most clearly demonstrated in the Yellow River (Huang He) valley where large-scale drainage/irrigation canal and bank/levee building that commenced in the lower reaches by c. 2900–2700 cal. BP (Kidder and Liu, 2014). The emphasis on floodplain flood control infrastructure was a result of long-term increases in sedimentation caused by large populations farming with increasingly efficient technologies in the fragile environment of the Loess Plateau (Zhuang and Kidder, 2014). Indeed, by the Early Dynastic period (221 BC – AD 220), the dynamics of the lower Yellow River were as much a product of inadvertent and deliberate anthropogenic activities as by natural environmental processes (Zhuang and Kidder, 2014). In this and similar contexts where large-scale river engineering was carried out (e.g. Islamic Mesopotamia; Butzer, 2012), it is difficult to say whether human or climate processes were more consequential. Anthropogenic landscape management and transformation frequently results in a greater risk of large-scale social and political collapse following massive floods or severe droughts, as communities become increasingly 'locked in' to their environment by the creation, development and dependence on physical infrastructure (cf. Kidder and Liu, 2014).

4. How floodwaters spread and recede

The inundation of floodplains is more than a simple matter of overtopping riverbanks (Lewin and Hughes, 1980; Mertes, 1997; Schumann et al., 2009; Trigg et al., 2012). Initial stages involve the penetration of lower bank-breaching points, and waters are often funnelled through these and then along floodplain depressions that follow swales and the lines of old channels. On some major river systems, there are also natural networks of active secondary floodplain channels (Paira and Drago, 2007; Lewin and Ashworth, 2014a, 2014b). These take off fine sediments and floodwaters, and it is they rather than the main river that may be responsible for sedimentation and water distribution on the floodplain itself, including the infilling of lacustrine environments. To start with, flows from both accessory and main channels may also be oriented at right angles to rivers down the back slopes of their levees. As water levels rise and fan out across floodplains, there are usually zones of high velocity and deeper flow; directions and velocities vary with river stage, and these may follow contrasting spreading and return-flow sequences during an inundation cycle. Significant flooding may also be achieved by subsurface flow and groundwater rise without physical connection to the channel, whilst as floods wane surface waters may drain away through evaporation and infiltration over a long-extended period. It takes a large and long-lasting flood for overbank flows to drown out the effects of floodplain topography to follow anything resembling a simple down-valley trajectory.

For early cultivators, moderate out-of-channel flows that occurred predictability, and then infiltrated to allow crops to grow and be harvested, were the most desirable. They were the safest, easiest to manage and divert. Local flooding circumstances were highly variable, as summarized diagrammatically in Fig. 3. This could involve: (a) flows along smaller secondary channels; (b) flows down levee back-slopes, and linear crevasse channels and splays;

Table 2
Present-day alluvial environments at selected reaches in the Nile, Indus, Huang He, Euphrates and Tigris valleys.

	Present channel width (m)	Valley gradient (m km^{-1})	Alluvial width[1] (km)	Channel style[2]	Floodplain character[3]	Avulsions or abandonment[4]
The Nile						
Dongola	600–800	0.31	14	s,c,i	f	d
Luxor	400–600	0.16	9	s,c,i	t,p,n	c
Giza	250–600	0.74	8	s,c,i	t,p,b	
The Indus						
Mohenjo Daro	600–1600	0.10	90	b,c,i	t,p	c
Harappa[5]	140–280	0.19	158	b,c,i	t,f	a,c
Huang He						
Zhengzhou	900–1500	1.00	50	b/m	t,b	a
Dong Ming	600–2000	0.13	160	m	t,b	a
The Euphrates (Nahr al Furăt)						
Raqqa	170–340	0.47	5	m,c,i	t,p	c
Babylon	90–110	0.10	110	s	c,b	
Ur [5]	110–160	–	166	s,a?	(disturbed)	a
The Tigris (Nahr Dijlah)						
Nimrud	150–250	0.31	3	m,c	t,p	c
Ctesiphon	180–340	0.12	40	m	c,l,b	c

Notes
1. Alluvial widths relate to the historical migration and alluviation plain between steeper valley edges. Because of incision and later changes, this may be greater than that of present rivers. Available alluvial widths, and potential channel relocation, in the lower Euphrates, Tigris and Indus are minimum figures.
2. Channels are categorized as braided (b), meandering actively (m) or relatively stable (s), or anastomosing (a). Islands (i) or prominent channel bars (c) may be present.
3. Floodplains may be tabular (t), convex (c), with palaeochannels (p) or flood-out channels (f), or with marginal lakes (l) or wetlands (w). Natural levees (if significant) are characterized as broad (b) or narrow (n).
4. Avulsive channel relocations (a), floodout channel desiccation (d), or cutoffs (c) which probably occurred during ancient occupation periods.
5. Channel not now at archaeological site.

(c) isolated ponds and lakes recharged either by flood flows or groundwater rise. Falling river stage provided channel- and pond-margins for cultivation (receding-flood or 'décrue' agriculture, rather than channel irrigation) alongside quasi-permanent lakes that offered a wide range of wild food and material resources; (d) temporarily stored waters in larger but shallow floodbasins which abate or could be drained to give a prolonged growing season; and (e) distributary channels and floodouts, both on fans and penetrating otherwise dry terrain on large floodplains for many kilometres. These can also provide shallow groundwaters even after surface flows had ceased (cf. Macklin et al., 2013b).

Flooding is a threshold phenomenon; flood flows vary to give sequences of extremes over decadal timescales even without climatic change. In hydrological terms flood timing and size can rarely be forecast from year-to-year, and overbank flows have to fall within a relatively narrow constrained range to be useful yet not seriously damaging. Historically, regulating measures rapidly became desirable. Small-scale early developments included the use of impounding dams across small channels (van Liere, 1980), the mechanical lifting of water out of channels (Butzer, 1976), and new channels directing flows to cultivated and urban areas (Adams and Nissen, 1972). Much larger scale and labour-intensive engineering works, involving major irrigation canals and drainage channels to enhance initial site advantages, or even to move cultivation into new areas, became practical at a later stage once societies and their economies had the prosperity, organisational capability and resources to undertake them. These in turn modified surface flows and groundwater regimes (Heyvaert et al., 2011). In some circumstances this led on to salinization, accelerated deposition in low-gradient artificial channels, and the creation of disease-prone environments (Smith et al., 2013).

5. Early civilizations in their river environments

The evaluation of environmental stresses both in the past and at the present day needs to be undertaken in light of contemporary riverine processes and how these impacted on riverine communities, as well as the effects of climatic change and occupational practices. This may be illustrated by a consideration of the river environments of early civilizations in the Nile Valley, where there is now an exceptional dated record of climate change, hydromorphological response and human settlement.

5.1. Nile catchment and hydrology

The River Nile is a mega-basin. Its channel network and alluvial record span >35° of latitude from just south of the equator to the shores of the Mediterranean Sea. At c. 3 million km^2, it is the world's second largest and most geographically varied river basin. The Nile's flow regime integrates two parts of the global climate system: the NH summer monsoon, and equatorial rainfall in the ITCZ (Macklin et al., 2013b). Changes in the flux of water and sediment to the Egyptian and Nubian Desert Nile and summer flooding are predominately controlled by climate in the Blue Nile/Atbara catchments, primarily the northerly extent and intensity of the monsoon. Winter and low flow levels in the desert Nile are controlled by equatorial precipitation over the While Nile catchment. Sedimentary sequences from Lake Victoria (Stager et al., 2003) and Tana (Marshall et al., 2011) provide long-term proxy records of flow in the White and Blue Nile, respectively (Fig. 4). River flow was recorded at Dongola in the Desert Nile for much of the 20th century (1910–1990) (Fig. 5A). The timing of peak flow from to year-to-year was regular and showed relatively little variation during the period of instrumentation. Conway (2000) analysing a time series of annual river flow of the Blue Nile and the Nile at Dongola showed there were significant and abrupt changes (by 20–40%) in peak Nile flow recorded at 1895 and 1975. These flow shifts indicate non-stationarity over centennial to multi-decadal time periods with river flow, in this instance, being relatively stable only over periods approaching 70 years (Conway, 2000).

Fluctuations in the Nile from the 7th until the early 20th centuries (AD 622–1922) are documented in historical measurements of the Nile flow levels at the Roda Nilometer opposite Old Cairo (Hassan, 1981). These historical records of low and high water

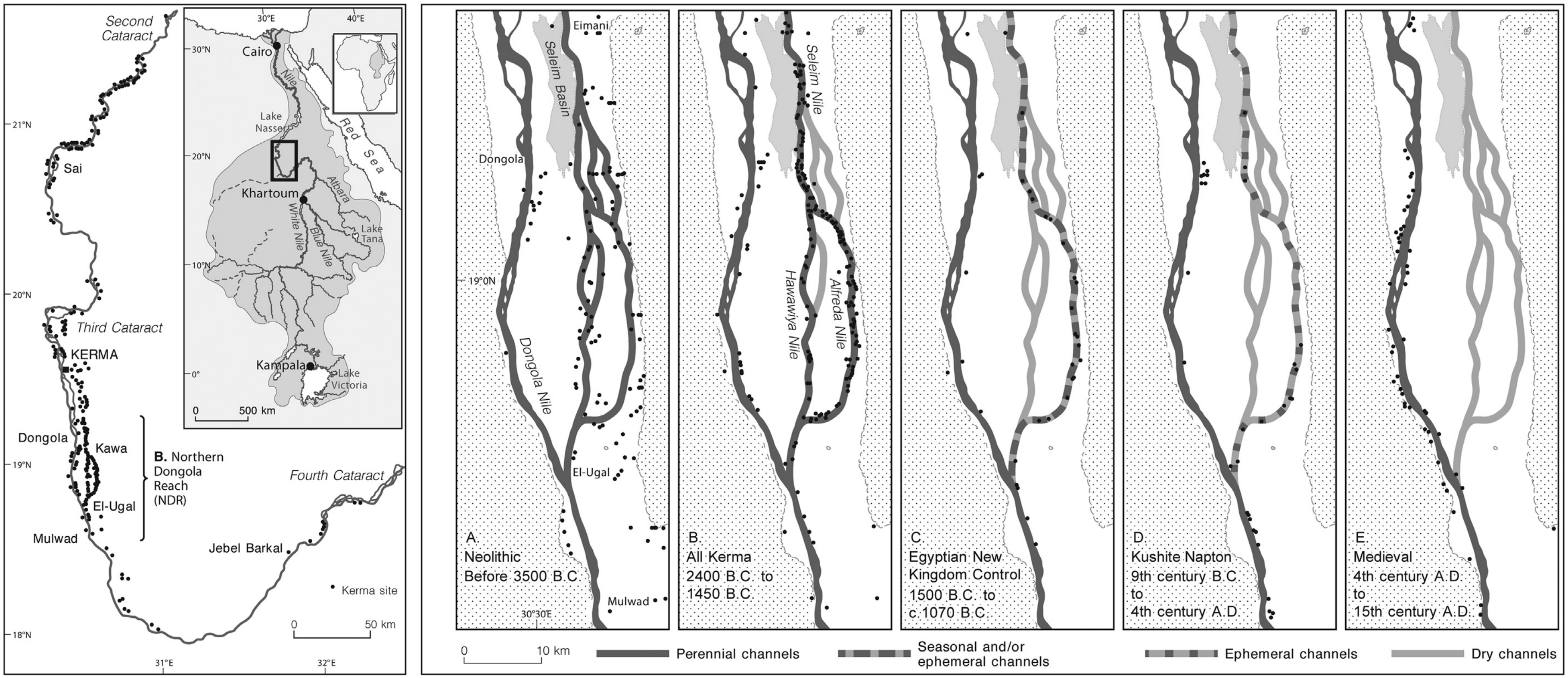


Fig. 6. Kerma sites between the Second and Fourth Cataracts of the Nile Catchment (left) and (right) Neolithic to Medieval archaeology and Holocene river dynamics in the Northern Dongola Reach (Macklin et al., 2013b).

levels (Fig. 5B) are among the longest hydrological series in the world that have near annual resolution (Kondrashov et al., 2005). Analysis reveals several statistically significant features in the record. These include a 256 year cycle, additional periodicities of 64, 19, 12 and 7 years and, most striking, quasi-quadrennial (4.2 year) and quasi-biennial modes (2.2 year) that support the long established connection between Nile River discharge and ENSO in the Indo-Pacific ocean. The cold – La Niña – phase of ENSO is associated with a more intense Ethiopian Monsoon and increased erosion and flow from the Blue Nile catchment, and El Niño years are characterised by periods of reduced flow and drought (Marriner et al., 2012). The longest periods may be of astronomical/solar origin but the 7 year cycle seems to be due to Atlantic influences, and possibly may be the origin cycle of runs of 'lean' and 'fat' years as mentioned in the biblical story of Joseph. However, the relationship between the NAO and Nile flow is not a straightforward one with periods of positive NAO during the Medieval Climate Anomaly associated with both high and low flow discharge (Hassan, 2007).

Long term (multi-centennial and millennial) changes in Nile flow during the Holocene are related to precession driven latitudinal migration of the ITCZ. Recently Marriner et al. (2012) have reconstructed extended hydrological time series from the Nile delta's Holocene sedimentary record showing sub-millennial secular changes in Nile hydrology linked to ENSO variability superimposed on the first-order low-latitude insolation forcing trend (Marriner et al., 2012). Most importantly, this study shows extended periods characterised by coupling between the Nile delta hydrology and high ENSO-like variance at c. 7000–4600 and 2500 cal. BP to the present, as well as a phase at c. 4600–2500 cal. BP where non-ENSO climatic factors provided the pace-maker for fluvial sedimentation (Fig. 4).

5.2. *Upper and Middle Egypt*

From Aswan to Memphis, the Nile flows within a well-defined floodplain of somewhat variable width for over 600 km. At Aswan, the valley floor is barely 2 km wide, but on average it is c. 10 km in width for much of the valley above the delta. Valley gradients are low (<10 cm km^{-1} in places) but again with slightly steeper reaches (See Table 2). Modern alluvial sediments are deposited within a valley trough that was excavated in relation to a low-level Messinian sea level in the Mediterranean (c. 5.6–5.3 Ma). This was subsequently refilled with sediments from the Pliocene onwards (associated with Red Sea tectonics) and then re-excavated. In the Pleistocene this valley floor gradually aggraded with sands and gravel, and finally during the Holocene with dominantly fine sediment derived from distant sources (Said, 1993). As Butzer pointed out (Butzer, 1976), this produced a seasonally inundated, freely-draining 'convex' floodplain with levees dominated by overbank sedimentation, not quasi-permanent swamplands. Additionally, there were secondary channels with levees, including the Bahr Yusef with a higher degree of sinuosity than the Nile itself. Under natural circumstances floodbasins became water-filled in sequence downvalley, up to a depth of around 1.5 m. In Upper Egypt, these were grouped into 22 nomes or administrative districts. Narrower floodplain stretches are said to have been characterized by greater populations, perhaps because flooding there was easier to manage. In exceptional flood years, basins could be drowned out and amalgamated; in dry years individual floodbasins might remain dry (Butzer, 1976, especially pp.15–18, 99ff.).

Early-stage management would presumably have involved the creation or improvement of levee-breaching (crevasse) channels, re-directing water from floodplain channels or ponded water into cultivation fields, and out-of-channel regulation by control structures and artificial levees. Canal cutting and diking (by First Dynasty times, c. 3000–2890 BC) permitted a greater degree of floodwater control. Later shaduf raising of river water by the Eighteenth Dynasty (c. 1550–1295 BC) allowed a degree of non-flood cultivation on levees themselves. This engineering appears to have been balanced by extensive crop storage to guard against deficiency in poor years, thus giving considerable actual and psychological power to central authorities, both kingly and religious. Runs of dry years damaged reputations and governance.

Butzer (1958) and Bell (1971) were among the earliest to appreciate the significance of dated flood and drought episodes; Bell concluded that dry 'Dark Ages' at c. 2180–2130 BC and 2000–1990 BC were widespread in the Middle East. Text references are not of course consistently available or precisely dated, and nor do 'troubled times' necessarily relate to river flood levels, which may not be specifically invoked. It may in fact not have been politic to blame the sacred Nile in any case (Bell, 1971, p. 13). Archaeological evidence for both spatial and temporal variations in inundation, together with a suggested eastward migration of the Nile, is reviewed in detail by Butzer (1976). He has pointed to both periods with extreme flooding (1840–1770 BC) and to dry periods such that the First Intermediate Period (c. 2160–2025 BC) saw catastrophic flood failure (see also Stanley et al., 2003), whereas the Ptolomies (332–30 BC) were favoured with beneficial flood regimes. Levee elevation and floodbasin depths were not large and relatively small differences in flood level could be of considerable significance. Bell (1970) also reconstructed flood heights as indicated by level marks on a now fallen and fragmented stele, and identified an average decline in flood levels between Dynasty I (c. 3000–2890 BC) and Dynasty II (2890–2686 BC). This is also evident by falling water level during this period in both Lake Tana and the Nile Delta (Fig. 4), suggesting a weakening summer monsoon. By contrast, Dynasty XII (c. 1985–1773 BC) seems to have been a period of high floods that then declined with Dynasty XIII (1773–1650 BC) (Bell, 1975).

More recent research has also placed emphasis on river channel changes, specifically in the Luxor region (Hillier et al., 2007; Bunbury et al., 2008, 2009; Ghilardi and Boraik, 2011) and most recently at Giza (Butzer et al., 2013). Lateral migration together with the formation of sandbars, islands and then secondary channel infilling has been identified. Long-lived islands, formed initially as sand bars but then vegetated and existing for centuries, are common on large rivers (Ashworth and Lewin, 2012); these may subsequently become attached and incorporated into the broader floodplain but initially may have been significant settlement foci for symbolic and practical reasons. However, following detailed sedimentological research, Ghilardi and Boraik (2011) contrary to earlier investigations that suggested that there was an island around the early Pharaonic complex at Luxor, show that there was intermittent aeolian and fluvial sedimentation at the site next to a more deeply incised river. Sandy levees or 'turtle backs' of mixed Nile sediment and aeolian materials were favoured as sites for early settlers; these later turned into protected islands, with abundant floods during the New Kingdom. Additionally, metres of sedimentation and lateral shift over the last 3500 years or so have transformed the floodplain landscape. Ghilardi and Boraik (2011) also identified flooding episodes in the sedimentary record at c. 1450 BC and c. AD 150–300. Butzer et al.'s (2013) urban geoarchaeological investigations of the Lost City of the Pyramids (Heit el-Ghurab), at the desert and floodplain margin of Giza, have shown evidence of major wadi floods c. 2565–2509 cal. BC and during the Islamic Middle Ages, with Nile floods demonstrably higher at c. 700 cal. BC and again during the 7th century AD to a climax at c. AD 700.

Overall, the Nile valley of Upper and Middle Egypt was dominantly of Type C flooding styles (Fig. 3C) – levees and floodplains – though with an element of channel mobility. This quite exceptional

Table 3
Hydromorphic environmental challenges to Old World river civilizations.

	A	B	C	D	E
	Fans & aprons	Mobile rivers	Levees & basins	Avulsive & floodout environments	Lacustrine wetlands
Acute					
1. extreme floods	*	*	*	*	*
2. droughts	*	*	*	*	*
3. channel shift	*	*		*	
Chronic					
4. sedimentation				*	
5. salinization			*	*	*
6. stream incision	*	*			
7. water-related disease			*		*

River	Morphology	Challenges
Nubian Nile, Dongola	D	1,**2**,3
Egyptian Nile, Upper Egypt	B/C	**1**,**2**,3,5,7
Indus, Mohenjo Daro	B	**1**,**2**,**3**
Ghaggar-Hakra	A/D	1,**2**,**3**,4,5
Huang He	D	**1**,2,**3**,4,5
Tigris/Euphrates (upper)	B	1,2,**3**,6
Tigris/Euphrates (lower)	D/E	**1**,2,3,4,**5**,**7**

Most threatening challenges in bold font.

geological and hydrological context (relatively stable channels within a long trough valley infilling with exotic fine sediment generated by a predictable monsoon-controlled seasonal flood regime) provided, as it does today, an enduring platform for floodwater farming supported civilizations, though one that remained sensitive to local channel and floodplain change, as well as annual/decadal-scale climatic fluctuations. Shallow flood basins were not permanently swamped by local precipitation as on many world rivers outside dryland environments, and the major river was both navigable and relatively unchanging over millennia.

5.3. Nubia

The southern border of ancient Egypt was traditionally located at the first (northernmost) Nile cataract at Aswan, which separated Pharaonic Egypt from Nubia, a culturally and geographically distinct region (Fig. 6). In terms of its geomorphology, the Nubian Nile differs significantly from the Egyptian Nile Valley with bands of hard igneous and metamorphic rocks intersecting the river creating six cataracts with shallows and rapids. In these reaches the rocky river bed and high water velocities makes navigation difficult or treacherous for much of the year except during the flood season. Between the cataract zones are a series of large depositional basins that can exceed 20 km in width and extend in length for more than 100 km. Within many of these valley floor expansion zones, but most notably in the Northern Dongola Reach (NDR) (Fig. 6) between the 3rd and 4th Cataracts, a sequence of well-preserved anabranching palaeochannels are preserved (Woodward et al., 2001). In the NDR palaeochannel belts are between 1 and 3 km wide and individual anabranches are convex in cross section with levees c. 2 m above the valley floor. Many hundreds of archaeological sites ranging in age from Neolithic (pre 3500 cal. BC) to Kushite (9th century BC to 4th century AD) are preserved adjacent to these channels and most often located on former levees (Macklin et al., 2013b).

By the second half of the third millennium BC, some 700 km of the Nile Valley between the 2nd and 4th Cataracts became the focus of a remarkable Bronze Age kingdom that was to dominate the region for the next 1000 years. Various names for the Bronze Age peoples of this region have come down from Egyptian texts but they are most widely known as the people of Kush (Edwards, 2004). The Kingdom of Kush's centre was a large settlement and religious site close to the modern Kerma and this has given its name to sub-Saharan Africa's earliest polity. The metropolis at Kerma was supported by a fertile hinterland, centred on the NDR, with anabranching channels ideally suited to irrigation-based agriculture and livestock rearing (Welsby et al., 2002). Since the mid-1990s the NDR has been the subject of detailed archaeological and geomorphological investigations, and presently constitutes the most well-dated and documented record of people-river environment interactions over the last 8000 years in the Desert Nile. Three major palaeochannel systems have been mapped up to 18 km east of the modern Dongola Nile (Fig. 6). OSL dating of fluvial and aeolian sediments infilling the systems has established when these channels were active, when they dried up and how this affected floodwater farming and settlement patterns in the region. Neolithic sites (5000–3500 cal. BC) are widely distributed across the valley floor reflecting more humid conditions, higher river flows and, as a consequence of a stronger summer monsoon, a more extensive channel network at that time. Operating together these would have significantly increased the amount of land available for seluka cultivation (the cultivation of land between high- and low-flow stages) without the need for irrigation (Welsby et al., 2002).

With the emergence of the Kerma culture c. 2400 BC, the number and locations of permanent settlements in the NDR changed radically. As the channel network contracted between 3500 and 2400 cal. BC there was shift of settlements to levees on the Alfreda and Seleim channels and the development of floodwater irrigation in adjacent lower-lying floodbasins (Fig. 6). In contrast to Pharaonic Egypt, the Kingdom of Kush flourished during the First Intermediate Period (c. 2160–2025 BC) environmental crisis with the number of settlements actually increasing between 2050 and 1750 cal. BC (Fig. 4D). Following the destruction of the Kushite state by Thutmose III (1479–1425 BC), and during the period of Egyptian New Kingdom control, there was abandonment of sites in the Hawawiya Nile (Fig. 6) and a marked reduction in the number of settlements in the Alfreda-Seleim and Dongola channel belts. OSL dating of aeolian sands infilling the Alfreda palaeochannel shows that the channel belt first dried up completely shortly before 1290 BC. This indicates that in little over a century after the Egyptian invasion, a climate-related failure of a major (>100-km-long) channel belt in the NDR, the flow of which had supported floodwater farming in the region since the Neolithic.

In the Dongola reach after the conquest of Kerma during the New Kingdom there is virtually no archaeological material from the late second millennium BC to early centuries of the first millennium BC with little evidence of any Egyptian activity in the region after 1200 BC (Edwards, 2004). However by the 8th century BC, the Dongola reach was the focus of a political revival that established a new Kushite Kingdom in the region. Centred on the Napata region of the Dongola reach more than 350 km up-river from Kerma, this kingdom was on a much larger scale than any previous polity in the region. Its rulers during the mid-8th century BC conquered and ruled over most of Egypt (XXV Dynasty) until the Assyrians expelled them in 650 BC (Edwards, 2004). This Kushite Kingdom is divided into two periods – the Napatan (c. 760–300 BC) and the Meroitic (c. 300 BC–AD 350) with the shift from the royal cemeteries from the Napata region to Meroe (located between the 5th and 6th Cataracts c. 200 km south-east of Napata) around 300 BC marking the division between these two periods (Edwards, 2004). Meroe is in the northernmost region of Sudan which at the present day receives annual summer rains.

In the NDR between the period of Egyptian New Kingdom control (c. 1500–1070 BC) and the Napatan (9th to 4th century BC) site numbers continued to fall in the Alfreda and Seleim channel systems (Fig. 6), and by the end of the 4th century BC these areas were abandoned. All major settlements have been located on the Dongola Nile itself since the 4th century AD. Both historical and OSL-dated sedimentological evidence in the NDR (Macklin et al., 2013b) and at Amara West (located between the 2nd and 3rd Cataracts) (Spencer et al., 2012), as well as in the Egyptian Nile at Giza (Butzer et al., 2013), identify a period of unusually large floods between the 8th and 5th centuries BC with channels drying up again by the 3rd century BC (Spencer et al., 2012). This multi-centennial episode of increased flooding in the Desert Nile during the Napatan was followed by an abrupt reduction in flow during the 3rd–4th century BC, which is also recorded in the lower Nile Valley at Lake Faiyum (Fig. 4E) and in the Nile Delta (Fig. 4G). In the Dongola reach of the Nile between the 3rd and 4th Cataracts, this permanent reduction in flow would have made floodwater farming impractical in all of the former Kerma and Napatan agriculturally productive floodplains beyond the margin of the present Nile. Indeed, the shift of the Kushite capital from Napata to Meroe at 300 BC coincides with a major hydroclimatic change in the Nile Valley, and Delta, and may have been a factor in its relocation to a region where rain fed agriculture was still possible.

The Nubian Nile, particularly within the NDR, demonstrates very clearly the intimate relationship between floodwater farmers, changing hydromorphology and the dramatic, sometimes catastrophic effects that abrupt climate-related changes of river flow had on irrigation-based agriculturists. Documenting and dating periods of channel and floodplain contraction in the major alluvial basins of the Desert Nile is seen as being critical for understanding long- and short-term people-river interactions in this and many other Old World dryland environments that supported ancient potamic civilizations.

6. Environmental challenges to Old World river civilizations

Table 3 summarizes the acute and chronic challenges which the early civilizations here discussed had to face. Perhaps paradoxically, just as there is now a general understanding that local climates respond to global-scale forcing, so it is also evident that hydromorphic changes impacted in contrasting ways at different locations. As far as early civilizations were concerned, this is not least because change is manifested through alluvial system response. Deciphering the effects of allogenic climatic change is complicated by the fact that autogenic changes (such as channel shifts, avulsions and island-formation) were also taking place at the same time.

Climate change proxies (Fig. 4) suggest that Holocene environmental changes on three timescales are likely to have been significant. First there are multi-millenial trends such as a long-term decline in African, Indian, and East Asian monsoon precipitation. This means that whilst river-based civilizations could have started under favourable conditions, these did not persist. Eventually some threshold – largely of aridity – was reached and there were only 'windows of opportunity' set between the onset of civic society development and the decline in its environmental context. Second, there appear to be millenial and multi-centennial scale periods when water availability status may have been favourable. An excellent example of this is the Bronze Age Kingdom of Kush (c. 2400–1450 BC) in the Northern Dongola reach of the Desert Nile. This flourished for 1000 years until its rapid demise at c. 1450 BC with invasion by Pharaonic Egypt, followed within a century by a castrophic reduction in Nile flows that led to the permanent abandonment of irrigated floodplains between the 3rd and 4th Cataracts (Macklin et al., 2013b). Third, there do appear to be shorter climatic 'aberations', such as the drought episode which affected greater Mesopotamia, Egypt and Indus Valley at c. 2000 BC (Weiss et al., 1993; Stanley et al., 2003; Giosan et al., 2012; Macklin et al., 2013b). A fourth element, for which the chronological precision of most hydrological proxy records are presently too coarse, is the impact of individual large floods or drought periods that lasted for a run of a few years. These could be both acutely destructive and politically destabilizing if food storage was inadequate. But considerable caution should be exercised in using periods even as long as the last millennium as a model for river hydrology and environmental behaviour for earlier periods. For example, recorded or estimated flows on the Nile (Fig. 5) now do not appear to be representative of earlier millennia given longer-term Holocene trends and non-stationarity in hydroclimate.

What also was of most use to the earliest cultivators was not simply the major rivers themselves but secondary flooding environments: flood-out channels, levees, accessory channel systems, ephemeral alluvial floodbasins and the margins of ponded waterbodies which fluctuated in level. These were safer to exploit initially and later easier to develop and extend with irrigation and drainage channels. Given the nature of known climatic fluctuations, it is suggested that certain environments were more susceptible to climatic changes lasting a decade or more than others, most notable of which were the distributed waters of the Nubian Nile (Macklin et al., 2013b) and the Indus and its tributaries (Giosan et al., 2012). In others, extreme climatic events (especially exceptional floods) may have had a more decisive effect, because these were avulsion-prone environments, as in Mesopotamia (Morozova, 2005) and on the Hwang He (Chen et al., 2012).

Spatial patterns of agricultural development reflected the topography of irrigation/wetland farming lands. In some circumstances there were strong directional gradients within flooding alluvial environments (as radially on fans, or down the backslope of wider levees), but in others water distribution systems radiated from artificially-engineered dispersion points with much less topographical constraint (e.g. Heyvaert et al., 2011) Whilst emphasis is often rightly placed on the sophistication of early engineering, this also followed a kind of 'design with nature' approach, as in the exploitation of secondary channels, crevass splays and floodouts which were already in place. But these sub-environments were also variably sensitive to floods and droughts, to channel shifts, and to salinity, health and sedimentation problems arising from high rates of evaporation in stilled waters. Controlled and stagnant water is desirably non-erosive, but its artificial creation may later bring health and salinity problems given the arrival of disease vectors or the local geologically controlled saline water and sediment sources.

Returning to Table 3, it is clear that river civilizations that have been discussed are liable to acute threats from floods and droughts. These may have been more or less common under periods of climate that were different from those of today. Certain environments (fans, laterally-mobile and avulsive rivers) also had acute channel change challenges responding to extreme floods that were autogenic and threshold in nature, and therefore not simply relatable to climate change. Longer term chronic stresses may result from century to millennial-scale climatic fluctuations: increasing aridity, for example, terminating once-favourable conditions for floodwater farming.

Other chronic threats were related in part to human activity itself, as with sedimentation from farming related soil erosion, salinization and the spread of disease through stagnant water environments. For example, the artificially enhanced spread of sediment into the once more common and wildlife-rich lacustrine environments in Mesopotamia led to their infilling and then to salinization; when irrigation failed, such fine sediments were liable to deflation (Wilkinson, 2003) so that the whole hydromorphological system has now been altered. Zhuang and Kidder

(2014) for the Huang He have similarly pointed to the roles of both inadvertent and deliberate anthropogenic activities in modifying the activities of natural processes, and this before the third millennium BC. Some technologies, such as the raising of water via wheel, chain or screw devices (saqiya and Archimedes' screw) or balanced buckets (shaduf), are likely to have had more limited hydromorphic impact. A general conclusion must be that environmental factors either for the development or the decline of river civilisations were indeed important, but that these are far from simple to unravel, partly because of the range of contemporary and subsequent human impacts, but also particularly as allogenic climatic changes on a range of timescales are mediated though the local autogenic activity of rivers.

7. Conclusions

This paper provides the first systematic overview of hydromorphic regimes that underpinned Old World river-based civilizations. Focussing on the Nile Valley, we have shown that Holocene climatic change impacted differently by region, whilst the dynamics of river environments were equally varied with local channel and floodplain change affecting human settlement and floodwater farming. To evaluate the effects of hydrology-related environmental change on riverine societies it is essential that the flow and sediment dynamics of the impacted channel and floodplain system are understood, and for local fluvial sedimentary archives, archaeological sites and settlement histories to be independently and well dated. Even for the River Nile that has one of the longest instrumental flow records in the world, 'short' (1000 yr) runs of historical data can be misleading as a guide to earlier flow regimes. Channel abandonment was a major problem for all Old World civilizations and this has been commonly attributed to avulsions following large floods. In these circumstances a simple association of extreme hydrological events with hydroclimatic change may not always be justified. However, recent research in the Nile (Macklin et al., 2013b) and Indus (Giosan et al., 2012) Valleys indicates that channel contraction and retraction resulting from abrupt and permanent climate-related reductions in river flow was the primary cause of the failure of floodwater farming and large-scale settlement abandonment. In these and in other dryland river environments elsewhere in the world that were the centres of early river civilizations (e.g. Mesopotamia, Central Asia), climate forcing rather than autogenic river processes may well have played a key role in the success, or otherwise, of riverine communities. Future research needs to continue to prioritise multidisciplinary studies in these regions in order that *both* river development *and* human settlement histories are constrained chronologically at least with centennial-scale resolution.

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