Quaternary Science Reviews 130 (2015) 109–123

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A new model of river dynamics, hydroclimatic change and human settlement in the Nile Valley derived from meta-analysis of the Holocene fluvial archive

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ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
15 September 2015
Accepted 30 September 2015
Available online 10 October 2015

Keywords:
Nile catchment and delta
Holocene climate change
Flooding
Drought
Channel and floodplain contraction phases
River civilizations

ABSTRACT

In the Nile catchment, a growing number of site- and reach-based studies employ radiocarbon and, more recently, OSL dating to reconstruct Holocene river histories, but there has been no attempt to critically evaluate and synthesise these data at the catchment scale. We present the first meta-analysis of published and publically available radiocarbon and OSL dated Holocene fluvial units in the Nile catchment, including the delta region, and relate this to changing climate and river dynamics. Dated fluvial units are separated both geographically (into the Nile Delta and White, Blue, and Desert Nile sub-regions) and into depositional environment (floodplain and palaeochannel fills). Cumulative probability density frequency (CPDF) plots of floodplain and palaeochannel units show a striking inverse relationship during the Holocene, reflecting abrupt (<100 years) climate-related changes in flooding regime. The CPDF plot of dated floodplain units is interpreted as a record of over-bank river flows, whilst the CPDF plot of palaeochannel units reflect periods of major flooding associated with channel abandonment and contraction, as well as transitions to multi-centennial length episodes of greater aridity and low river flow. This analysis has identified major changes in river flow and dynamics in the Nile catchment with phases of channel and floodplain contraction at c. 6150–5750, 4400–4150, 3700–3450, 2700–2250, 1350–900, 800–550 cal. BC and cal. AD 1600, timeframes that mark shifts to new hydrological and geomorphological regimes. We discuss the impacts of these changing hydromorphological regimes upon riverine civilizations in the Nile Valley.

1. Introduction

The River Nile and its catchment are globally significant with respect to their river valley archaeology and geological archives of Quaternary climate change (Butzer and Hansen, 1968; Friedman, 2002; Woodward et al., 2007). Although there have been several studies that have integrated ^{14}C-dated Holocene lake histories in the Nile catchment (Butzer, 1976; Nicoll, 2001, 2004, 2012; Kuper and Kröpelin, 2006), Nile Delta (Marriner et al., 2012; Flaux et al., 2013) and offshore sedimentary records (Revel et al., 2010; Blanchet et al., 2013) to reconstruct regional Holocene palaeoclimates, outside of a few well-studied areas (the hyper arid

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http://dx.doi.org/10.1016/j.quascirev.2015.09.024
0277-3791/

Nubian Desert – Woodward et al., 2001; Macklin et al., 2013; the lower Blue and White Nile Valleys – Williams et al., 2000, 2010), the Holocene hydromorphological development of the River Nile Valley is surprisingly poorly documented. This has arisen for three primary reasons:

1) the difficulty of dating fluvial sediments using radiocarbon techniques as a consequence of the poor preservation of organic material, except at some archaeological sites;
2) the lack of high-resolution hydroclimate proxies independent of the Holocene fluvial archive that can be used to validate riverine-based reconstructions of environmental change; and
3) restrictions on the export of samples from Egypt for radiometric dating.

The development and first use of Optically Stimulated Luminescence (OSL) techniques in the late 1990s (Woodward et al., 2001) to date Holocene Nile alluvium in Sudan, however, has significantly improved our ability to construct robust fluvial chronologies in the region. This has led to a new understanding of the impact that climate-related changes in river hydrology had on floodwater agriculturists (Macklin et al., 2013).

Although there has been growing number of site- and reach-based studies employing ^{14}C and, more recently, OSL dating (e.g. Williams et al., 2010; Honegger and Williams, 2015), there has been no attempt to critically evaluate and synthesise these data at a catchment scale for the entire Holocene. This paper presents the first meta-analysis – the use of a systematic review procedure and common set of statistical techniques to combine the result of several studies (cf. Macklin et al., 2012a) – of published and publically available ^{14}C- and OSL-dated fluvial Holocene units in the Nile catchment and relate these to changing regional hydroclimates. From this new analysis, major changes in river flow, sedimentation and channel dynamics are identified and their potential impacts on riverine civilizations in the Nile Valley are discussed.

2. Study region

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 (Fig. 1). With an area of c. 3 million km^2, it is the world's second largest and most geographically varied river basin. Whilst it exhibits enormous diversity in climate, geology, ecosystems, and topography, five distinct landscape sectors can be recognised. These have been defined by Said (1981) and summarised by Woodward et al. (2007) as follows:

1) The densely vegetated equatorial lakes region in the ancient Nubian shield terrain of the White Nile headwaters.
2) The vast reed swamps of the Sudd in the middle reaches of the White Nile that can exceed >130,000 km^2 in the wet season.
3) The volcanic highlands and deep ravines of Ethiopia and Eritrea that form the headwaters of the Blue Nile and which produce very high sediment yields.
4) The great bends, cataracts and broader alluvial reaches of the Desert Nile corridor that extends from Khartoum through Sudan and Egypt towards Cairo.
5) The low-gradient Nile Delta and coastal zone, where sedimentation is strongly influenced by marine processes.

The flow regime of the Desert Nile integrates two fundamental elements of global climate: the Northern Hemisphere (NH) summer monsoon and equatorial rainfall in the Intertropical Convergence Zone (ITCZ) (Woodward et al., 2001; Macklin et al., 2013). The monsoon dominates the flow regime of the Blue Nile and Atbara Rivers whilst the ITCZ controls the flow regime of the White Nile. Furthermore, instrumental data show a clear link between flooding regimes and ENSO, principally with regards to the hydrology of the Blue Nile. El Niño is characterized by drought and a fall in Nile flow. By contrast, La Niña is characterized by strong rains and Nile flooding (Indeje et al., 2000; Ortlieb, 2004). During the Holocene, changes in the water and sediment yields of the White Nile and Blue Nile/Atbara rivers were governed by the climate of those basins. Water and sediment from these large headwater basins enter the Desert Nile in two places: 1) the Blue Nile/White Nile confluence at Khartoum (where the Desert Nile begins) and 2) where the Atbara River joins the Desert Nile 80 km upstream of the Fifth Cataract (Fig. 1). Recent work using strontium ratios has also shown the importance and sediment inputs from tributary wadis in Sudan and Egypt during the African Humid Period (Woodward et al., 2015a). The mean annual discharge of the modern Nile is typically about 88 ± km^3. This comprises 28 ± km^3 from the White Nile, 48 ± 10 km^3 from the Blue Nile, and 12 ± 5 km^3 from the Atbara (Padoan et al., 2011). The contributions from the Blue Nile and Atbara show marked seasonal variability; together they account for 90% of the summer flood (Williams and Adamson, 1982; Woodward et al., 2007).

The database assembled and presented in this paper is dominated by work on the fluvial sediments and landforms of the Desert Nile and, to a lesser extent, the delta (14% of all fluvial dates) (Fig. 2). It is in these desert sectors of the Nile basin, (particularly in northern Sudan) where records of long-term shifts in Holocene river behaviour resulting from changes in the flood regime and sediment yields of the major headwater basins are best preserved and well dated (Woodward et al., 2001; Williams et al., 2010; Spencer et al., 2012; Macklin et al., 2013).

3. Methodology

A database (see Suppl. Mat.) of published and publically available ^{14}C- and OSL-dated Holocene (<11,700 years cal. BP) fluvial units in the Nile catchment and Nile Delta was compiled using the guidelines set out by Johnstone et al. (2006). The creation of this database was an international collaboration by the authors of this paper. For the Nile Delta, only *fluvial* sand or silt units were included (as recorded by Marriner et al., 2012) in order to exclude the effects of marine processes on the fluvial sedimentary archive and to unequivocally identify sedimentary units generated solely by Nile floods. One hundred and fifteen fluvial units were identified; 66 dated by ^{14}C and 49 by OSL techniques (Fig. 2 and Suppl. Mat.). To avoid double counting of units, no duplicate dates were used. Radiocarbon ages were calibrated using INTCAL13 (Reimer et al., 2013). OSL dates were recalculated to calendar dates using the year of sample collection – error margins for OSL dates were distributed normally. Calendar ages, including 2σ error range, were summed using Oxcal C_Date modelling (Bronk Ramsey, 2001). Cumulative probability density functions (CPDF) were generated following recently published guidelines by Jones et al. (2015) for the combined analysis of ^{14}C- and OSL-dated fluvial units. Holocene fluvial units were subdivided geographically into the Nile Delta, the Desert Nile (downstream of Khartoum), the Blue and White Nile catchments, as well as into floodplain and palaeochannel depositional contexts. These classes were chosen for reasons of data availability. CPDFs were produced for the entire dataset, for ^{14}C- and OSL-dated fluvial units and three regions of the Nile basin (Desert Nile, Blue and White Nile catchments) and the Nile Delta.

Our exploratory meta-analysis approach is not intended to identify individual flood events but provides a probabilistic assessment of centennial-length and longer flooding episodes within individual catchments (Hoffman et al., 2008) as well as for