



Long-Term Urban and Population Trends in the Southern Mesopotamian Floodplains

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Abstract

The processes of long-term urbanization in southern Mesopotamia are still insufficiently investigated, even though recent studies using large datasets and focusing on neighboring regions have paved the way to understanding the critical role of multiple variables in the shaping of settlement strategies by ancient human societies, among which climate change played an important role. In this paper, we tackle these issues by analyzing, within the new FloodPlains Web GIS project, a conspicuous amount of archaeological evidence collected over the past decades at approximately 5000 sites in southern Mesopotamia. We have measured modifications over time in a variety of demographic proxies generated through probabilistic approaches: our results show that the rapid climate changes, especially those that occurred around 5.2, 4.2, and 3.2 ka BP, may have contributed—in addition to other socioeconomic factors—to triggering the main urban and demographic cycles in southern Mesopotamia and that each cycle is characterized by specific settlement strategies in terms of the distribution and the dimension of the urban centers.

Keywords Mesopotamia · Settlement patterns · Urbanization · Climate · Aoristic analysis · Demography

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Introduction

Numerous trajectories of development and collapse, population increase and decrease, the rise of early states, and the formation and fall of empires characterize critical segments of the human past in the Near East, yet to date they have not been properly framed. Blanton's statement from 1976 (p. 261) remains valid, in general: "traditional theories of cities ... fail because they cannot adequately account for the cross-cultural variability in the nature of cities, and because they are inadequate for dealing with the dynamic properties of cities and the societies of which they are a part." Many questions remain concerning the actual responses and feedback of ancient societies in the face of climatic variability and rapid environmental modifications. In this paper, we apply well-established palaeodemographic approaches to a new, updated, and comprehensive dataset for all the archaeological sites documented so far in southern Mesopotamia in order to improve our current understanding of long-term urban and population trends. We also provide suggestions to connect these trends, as well as their potential relationship with the climatic events that have occurred in historical times, to underlying social, political, and economic mechanisms.

The project from which this paper stems was conceived and developed to create an open platform (a Web GIS called FloodPlains) that is useful for the study of the human–environment interaction in a crucial area for global history, with an eye to sustainable development in terms of future archaeological landscape management, as part of the area under study is likely to be lost to rising sea levels in the next three decades. FloodPlains also intends to enhance data public accessibility, data integration, and the possibility of testing hypotheses on long-term trends, which are key to understanding local and regional dynamics that resonate with global issues as well.

Our quantitative analysis of large and controlled new datasets for southern Mesopotamia—the FloodPlains Web GIS and very recent surveys that have been studied in a collaborative way—offers an unprecedented long-term and geographically broad perspective within which to address three unanswered research questions on urban and population dynamics in southern Mesopotamia from the Late Chalcolithic I (c. 4300 BC) to the end of the Islamic period (c. AD 1250). What trends can be identified in the development of urbanized areas, and what was the relationship between urban centers and rural areas in the Mesopotamian floodplains? How do these processes reflect on, or can be interpreted in relation to, trends in population size and density? How did climate trends have a qualitative effect on quantitative demographic fluctuations?

A Region in Flux: Current Paradigms and Their Limits

The definition of the drivers, dynamics, and effects of long-term urbanization and demographic processes in ancient near eastern societies is a hotly debated topic (Algaze 2017; Lawrence et al. 2021a; Menze and Ur 2012; Palmisano

et al. 2021b; Wilkinson 2003). While multiple variables and countless methodologies have been applied to large geographic swaths in both the Old and New Worlds, the southern Mesopotamian floodplain, a crucial region in global history, still lacks a comprehensive understanding of the developmental processes that shaped its urban and rural landscapes over time, in part a consequence of the inherent dynamics of its complex riverine system that has been underappreciated until quite recently. We provide an overview of the paradigms that have emerged through time and of the current limits that affect our understanding of those processes in Southern Mesopotamia.

From Early Paradigms to Robert Adams' Research

Until the late 19th century AD, the floodplain of Mesopotamia was perceived as a paradigm for vanished, high civilizations leaving behind elusive vestiges in an abandoned landscape, compounding stagnation under Ottoman administration with a teleological vision of history in which civilization moved west (Liverani 2013). This narrative was also fitting for the site-centered approach of most archaeologists, which left little room for extra-urban explorations, except for mapping the location of previously undetected urban sites in view of their potential excavation (Adams 1962; Gibson 1972).

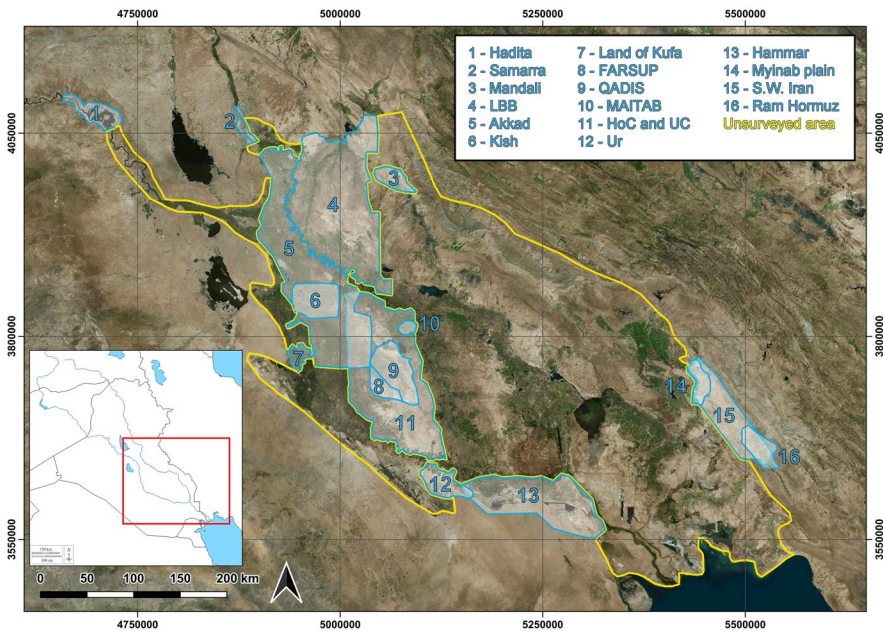


Fig. 1 Distribution of surveyed areas (blue) within the southern Mesopotamian floodplains (yellow). For the extension of those areas and the number of sites per each survey, see Table 1

Alternative scientific narratives developed only from the late 1950s, thanks to the large-scale archaeological datasets obtained from the first systematic archaeological survey projects (Fig. 1; Adams 1965, 1981; Adams and Nissen 1972), which also benefited from updated methodologies and new techniques (Adams 1962). By analyzing a dataset of about 2700 archaeological sites in the central and southern Mesopotamian floodplain, Adams (1981) proposed the first comprehensive reconstruction of settlement patterns, population size, and land use from the later sixth millennium BC to the Ottoman period (i.e., up to c. AD 1900). As emphasized by Levy (2019), such a novel research avenue was part of the new archaeology and made use of locational analyses and rank-size rules to test ideas of the evolving processes that led to growth, stability, and resilience in ancient Mesopotamian cultural systems. Adams' particularly open-minded approach also encompassed the analysis of many different historical sources, such as the Neo-Babylonian Murashu archive and the writings of the Roman historian Strabo (Adams 1965, 1981). Such a multidisciplinary vision, integrating archaeology with philology, aerial remote sensing, and geology, allowed him to pioneer modern studies on long-term urban and demographic trajectories in the so-called cradle of civilization over the course of six millennia.

In his analysis, Adams (1981) proposed to identify three major phases: the first one, defined as “urban origins” and lasting from the Ubaid (5500 BC) to the end of the Early Dynastic I period (2700 BC), was a formative period characterized by a growing capacity of water manipulation that culminated in the creation of a complex web of artificial canals, along which hundreds of cities and villages flourished and where massive agrarian exploitation of that new landscape took place. The albeit preliminary demographic data showed a gradual increase of population that might have greatly benefited from technological improvements.

These advances provided the foundations, during the second phase, for the development of new political entities, from the so-called Sumerian urban polities to the first empire under the Akkadian dynasty to the competing Babylonian kingdoms. For more than a thousand years (approximately 2700–1500 BC), these “successive contending dynasties” underwent periods of integration and fragmentation, expansion, and retreat resulting in substantial shifts of the Mesopotamian hydraulic landscape and settlement patterns. While Adams (1981) acknowledged the role of multiple factors such as climate fluctuations or societal changes, the main drivers triggering these fluid phenomena, according to Adams, lay in the changing political and economic trajectories of the ruling dynasties. This kind of interpretation may also have depended on the lack of fine-tuned data, especially as far as it concerned climate history, as well as from the patchy exploration of urban and, even more so, rural centers, which made it difficult to outline a material history of those societies. The collected data suggested that urban hierarchies would have varied according to the ruling dynasty, following a continuous back and forth between Ur, Lagash, Kish, Girsu, Akkad, Uruk, Isin, Larsa, Babylon, and other cities. Political instability corresponded to a series of demographic booms and busts that eventually ended with a prolonged phase of population decrease between 2000 and 1500 BC.

After this period of instability, the last phase was defined by Adams (1981) as the “culmination and collapse of an agrarian base and urban superstructure” (1500 BC–AD 1500). The first part of this long period saw an impressive increase of

settlements and a population spreading all over the floodplains. This was particularly apparent under the Parthian and Sasanian empires (approximately 200 BC–AD 600). In Adams' words (1981, p. 175) during this period “city-building, population density, and most other manifestations of complex, differentiated social life, centralized direction had attained levels transcending anything known earlier.” The Islamic conquest of the Mesopotamian floodplain (after AD 637) marked the emergence of a different approach to landscape exploitation. This was, in fact, characterized by proliferation of new rural settlements in previously empty areas and the extensive depopulation of others. Then by AD 1200, the shift of the Tigris Rivers coupled with the Mongol invasion, which resulted in the sack of Baghdad in AD 1258, left traces on the ground in the significant shrinking of previously large urban centers, rural villages, and water systems such as the one at Katul-Nahrawan.

Adams' pioneering study paved the way for a new understanding of the wider history of the Mesopotamian alluvium. However, his work had some limitations that were only partially overcome by subsequent studies. The first regards the dataset that, although of an unprecedented dimension for the time, covered only part of the southern Mesopotamia floodplain. Another one concerns the fact that the study of the ancient landscape, although based on aerial remote sensing, historical sources, and field surveys, did not yet benefit from the potential of disciplines such as geoaerchaeology, satellite remote sensing, archaeometry, and so on. In addition, although quite advanced, the system for dating sites was based on a knowledge of material culture that was still under development. As demonstrated by subsequent studies (Marchetti et al. 2017, 2019; Marchetti and Zaina 2020), some chronological attributions have proved inaccurate, thus influencing the final data interpretation.

After “Heartland of Cities:” Post-Adams Perspectives on the Mesopotamian Floodplains

To complement Adams' reconstruction, from the 1990s onward, new research lines and methodologies have emerged. These studies focused, above all, on the early historical phases of Mesopotamia with the aim of improving the understanding of the mechanisms of urban, demographic, political, and social development in the region (Aqrabi 2001; Baker 2022; Gasche and Tanret 1998; Larsen and Evans 1978; Pournelle 2003; Rost 2017; Ur 2006; Wilkinson 2003; Wilkinson et al. 2013). These approaches allowed scholars to better frame the impact of changes over time of the courses of the Euphrates and Tigris Rivers, of the differential intensity of control over waterways for agricultural purposes, and, although tentatively, of the Gulf transgression and progradation. As a result, the new narrative recognized that the current topography of the floodplain is the result of the slow accumulation of the sediments mainly from the Euphrates, Tigris, Diyala, and Karun Rivers (Jotheri et al. 2016; Rost 2017; Wilkinson 2003), along with the marine transgression caused by climate change during the Early–Middle Holocene (Aqrabi 2001; Kennett and Kennett 2006; Morozova 2005). This long-term process, together with a wide range of autogenic, allogenic, and human-induced actions triggered significant variations of the courses of the rivers and resulted in a physical landscape characterized by highly diversified geomorphological sectors (Fig. 2; Wilkinson 2003, pp. 76–78, fig. 5.3). From their initial location in the central part of the floodplain, where between 5500 and 3000 BC they contributed

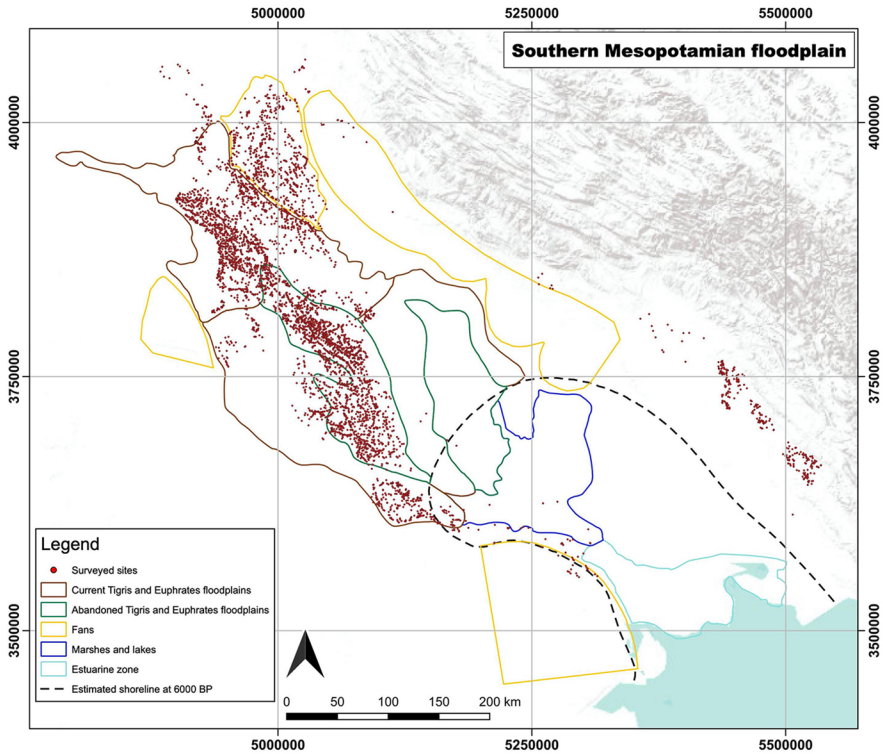


Fig. 2 The southern Mesopotamian settled floodplains within their geomorphological setting

to the development of the earliest states (Rost 2017; Wilkinson 2003), the main courses of the Euphrates and Tigris Rivers gradually shifted in opposite directions, increasing the extent of the alluvial area sandwiched between the Zagros Mountain and the Arabian Plateau (Jotheri et al. 2016). This phenomenon was intertwined with a remarkable climate instability that affected the region, with at least six periods of rapid climate change (Anderson et al. 2007). Scholars have started giving ever-growing attention to the key role of climate change in shaping the lifecycle of past societies, as confirmed by the numerous multidisciplinary initiatives conducted especially in northern Mesopotamia and the Levant (Kennett and Kennett 2006; Knodell et al. 2023; Lawrence et al. 2021b; Morozova 2005; Palmisano et al. 2021b; Staubwasser and Weiss 2006; Thompson and Zakhrirova 2021; Weiss 2017; Weiss et al. 1993).

The entangled flux of events discussed above had a primary role in influencing human decision-making and thus shaping the long-term urban and population dynamics in the region, ultimately depending on the adaptive strategies and resilience of Mesopotamian societies (Kennett and Kennett 2006; Weiss 2017). At the same time, palaeodemographic approaches have also been used in archaeology and evaluated against the backdrop of climate variations (Lawrence et al. 2021a,

b; Palmisano et al. 2021a, 2021b), while demographic studies on a global scale (Goldewijk et al. 2010; Modelski 2003; Reba et al. 2016; Stephens et al. 2019) have attempted to provide a general reconstruction of population trends through time. It is noteworthy that those very processes that have modified the environment and influenced settlement patterns and population dynamics in southern Iraq are still underway (Wilkinson and Hritz 2013) and will cause substantial modifications of the extension and morphology of the Mesopotamian floodplain in the near future due to the expected rise of sea levels (Kulp and Strauss 2019).

Issues remain, however, that still hamper a detailed historical reconstruction. In fact, current narratives on the long-term urban and demographic history of southern Mesopotamia (Baker 2022; Ur 2013; Wilkinson 2003; Wilkinson et al. 2013) still mostly rely on Adams' conclusions (1981), although chronological issues could have been significantly improved in light of the new discoveries and excavations carried out from the 1980s (see, e.g., projects listed in Anonymous 1991). As for demographic studies (Goldewijk et al. 2010; Modelski 2003; Reba et al. 2016; Stephens et al. 2019), we observe a partially flawed approach that addresses long-term historical issues on a global scale but sometimes without having solid datasets at local levels. Furthermore, the use of statistical approaches for simulating long-term trends has been only partially tested and almost only for the formative periods of Mesopotamian history (i.e., the fourth and third millennium BC; Wilkinson et al. 2013).

Assessing the Plains: An Overview of Current Research Lines and Methodologies

In this section, we provide a detailed discussion of the strengths and limitations of current research and methodologies for the study of long-term urban and demographic trends in Mesopotamia. The new season of research in and on southern Mesopotamia, which started approximately 20 years ago, has benefited from new methodologies and research questions already tested in other geographical areas. We identify five main multidisciplinary lines of research that are particularly contributing to the improvement of prior narratives, thus boosting our understanding of long-term urban and demographic trends in southern Mesopotamia: remote sensing analysis, geoarchaeological and palaeoenvironmental studies (Fig. 2), computational approaches, research on global demographic trends, and the resumption of surface investigations in the southern Mesopotamia floodplains during the 2010s (Table 1).

Reconstructing Archaeological Landscapes from Air and Space: Approaches to Remote Sensing

Remote sensing is the process of detecting and monitoring the physical characteristics of an area at a distance, typically from satellite or aircraft. Its application in archaeology (Lasaponara and Masini 2012; Parcak 2009; Wiseman and El-Baz 2007) represented a gamechanger in the study of the past, and it was part of a larger digital revolution that allowed the field to quickly improve the quantity and quality of research (Bevan 2015; McCoy 2017).

The first attempts at applying remote sensing in archaeology for the study of Near Eastern hydraulic landscapes date back to World War I with the use of military aerial

Table 1 Archaeological surveys carried out in the southern Mesopotamian floodplain region.

No.	Survey name	Years	Institution	Approx. area covered (km ²)	No. of sites*	References
1	Haditha dam	1978–1983	SBAH	945	38	Abdul-Amir 1988
2	Samarra	1983–1989	University of Paris 1	342	1	Northedge 2007; Northedge and Faulkner 1987
3	Mandali	1966–1967	University of Cambridge	724	12	Oates 1966, 1968
4	(LBB) Land Behind Baghdad	1957–1958	University of Chicago	11,548	867	Adams 1965, 1981
5-6	Akkad and Kish	1956–1957, 1966	University of Chicago	11,176	435	Adams and Nissen 1972; Gibson 1972
7	Land of Kufa	2019–2020	Universities of Kufa, Koç, Bologna	480	29	Maner et al. 2020
8	(FARSUP) Fara Regional Survey Project	2016–ongoing	University of Munich	573	62	Otto et al. 2018
9	QADIS	2016–2020	University of Bologna	1,800	146	Marchetti et al. 2017, 2019, 2020
10	Missione Archeologica Italiana a Tutul al Baqarat	2013–ongoing	CRAST Turin	215	42	Lippolis 2016, 2020
11	(HoC) Heartland of Cities and (UC) Uruk Countryside	1968–1975	University of Chicago	11,855	1544	Adams 1981; Adams and Nissen 1972
12	Ur	1966	University of Chicago	1,240	190	Wright 1969, 1981
13	Hammar lake	1953–1958, 2010	IPC, Universities of S. Carolina, Penn- State, Washington	6042	83	Hritz et al. 2012b, a; Roux 1960
14	Mynab plain	2001–2002	University of Sydney	723	131	Moghaddam and Miri 2003
15	South West Iran	2003–2005	University of Sydney	3565	53	Moghaddam and Miri 2007
16	Ram Hormuz	2005–2008	University of Chicago	975	108	Alizadeh 2014; Wright and Carter 2003

*The total number of sites is lower than the total number available on <https://floodplains.orientlab.net> because several major archaeological sites (Lagash, Girsu, Nigin, etc.) were not included in survey areas. The archaeological survey projects QADIS, FARSUP, MAITaB, and Land of Kufa provided us with partially yet unpublished data.

photography in the area of Samarra (Beazeley 1919). The abundance of evidence that could be recorded with aerial views, in an area where field surveys were complicated to be carried out systematically, was elevated by Adams to standard practice (Adams 1965, 1981). He used a set of aerial photographs made by KLM Dutch Airlines for the Iraqi Government (which cannot be located any more, see Pournelle 2007a, b, p. 40, n. 4), and during the 1970s, he decisively upgraded his approach by employing LANDSAT satellite imagery capable of covering the entire region under analysis. Adams appreciated the value of low-resolution satellite imagery (80 m) because the lack of detail made it easier to detect larger traces such as levee systems (Adams 1981, p. 33). However, it was not until 1996 that a crucial dataset for studying Near Eastern archaeological landscapes became available: the US CORONA satellite program imagery. Originally conceived and designed for military purposes, the CORONA satellite program was operated by the US Central Intelligence Agency between the late 1950s and early 1970s to map the world at an unprecedented scale and resolution. Together with other high-resolution photographic acquisition programs (KH-7 Gambit, KH-8 Gambit 3), CORONA provides a global-scale multi-temporal library of images that can be exploited for multiple purposes. This wealth of data was declassified by the US government between 1996 and 2013 and made publicly available for free (<https://earthexplorer.usgs.gov/>), thus opening a new season for the study of ancient landscapes. Their relevance for archaeological research was immediately recognized, allowing from the late 1990s (Kennedy 1998; Philip et al. 2002), the identification of new sites within regional survey areas (Casana and Wilkinson 2005; Kouchoukos 2001; Philip et al. 2002; Ur 2002), as well as the reconnaissance of field and channel systems (Casana and Cothren 2013; Hritz 2010; Philip and Bradbury 2010). In the last 20 years, the use of GIS software and high-resolution and publicly available satellite datasets (e.g., Google Earth, Bing, Copernicus, etc.) have, in fact, made the use of remote sensing an integral part of the archaeological landscape analysis (Gasche and Tanret 1998; Hritz 2004; Jotheri et al. 2019; Ur 2006; Wilkinson 2003). Today, the majority of regional survey projects have remote sensing analyses as their starting point: e.g., the Fragile Crescent project (Galiatsatos et al. 2009), the Ebla Chora project (Mantellini 2013; Marchetti 2018; Matthiae and Marchetti 2013), and much of the recent fieldwork in southern Mesopotamia discussed below.

The current breadth of remote sensing tools for documenting archaeological landscapes encompass spaceborne (satellites from approximately 150 km and upward), airborne (airplanes and helicopters ranging in height from a few hundred meters to 12 km), and ground-based vehicles (UAV or drones not exceeding 150 m) (Belward and Skøien 2015; Jeziorska 2019). The integrated use of these devices represented a step forward in the reconstruction of urban and rural historical landscapes in Mesopotamia and beyond. The dramatic increase in the use of aerial documentation carried out by means of UAVs has been a significant step forward in archaeological documentation, described as the “democratization of aerial archaeology” (Stefan and Stefan 2016, p. 25). However, the basic limitation of this methodology and tools lies in the fact that the information they provide must always be considered preliminary and requires validation on the field (Zaina and Tapete 2022).

Geoarchaeology and Paleoenvironmental Studies

One of the admittedly main limits of Adams' reconstruction of the Mesopotamian landscape development was the paucity of data regarding geology and climatology. These gaps have been slowly filled since the 1990s in much of the Near East, thanks to the more widespread diffusion and application of geoarchaeological and paleoenvironmental studies. Geoarchaeological analyses were widely applied starting two decades ago, when the historical development of water management in Mesopotamia was receiving increasing attention by scholars. This interest is linked to the relevance of the topic in the reconstruction of irrigation, transport systems, trade networks, and land management in ancient polities. While the first pioneering geoarchaeological studies conducted in the 1990s (Gasche and Tanret 1998; Verhoeven 1998; Wilkinson 1990) shed light on the hydraulic landscapes of the Mesopotamian floodplain, the consolidation of a multidisciplinary approach beginning in the early 2000s (Jotheri et al. 2016; Morozova 2005; Pournelle 2003; Rost 2017; Wilkinson 2003; Wilkinson et al. 2015; Wilkinson and Jotheri 2019) paved the way for a new season of research.

Currently, the geoarchaeological approach is not limited to the study of river courses but also involves research related to tectonics and sediments (Lemcke and Sturm 1996; Pournelle 2003; Yacoub 2011), climate fluctuations (Anderson et al. 2007; Palmisano et al. 2021b; Wilkinson and Hritz 2013), early harbors (Adams 2008; Di Giacomo and Scardozzi 2012; Hammer 2019; Romano and D'Agostino 2018; Stone and Zimansky 2004; Ur 2013), and the study of ancient coastlines (Kennett and Kennett 2006). However, current interpretations mostly rely on regional studies (Adams 1981; Aqrabi 2001; Jotheri et al. 2016; Pournelle 2003) and ample chronological phases, often working at a millennial scale (Jotheri et al. 2018; Morozova 2005; Wilkinson and Rayne 2010; Wilkinson et al. 2015). This is mostly due to the still limited data collected in terms of available cores and the patchy geographical distribution of the areas that have been studied in greater detail.

Paleoenvironmental studies certainly benefited from the increased interest in climate history at a global level. In this sense, archaeologists attempt to contribute to the wider debate by exploring how and when climatic changes occurred in the past and what adaptation strategies were implemented by humans (Edgeworth et al. 2014; Pétursdóttir 2017). In this regard, it is important to stress how climatic variations are part of the multiple, often interconnected and interacting factors that may have triggered the crisis and regeneration of Mesopotamian societies, according to what Hoyer et al. (2023) define as 'polycrisis.' Furthermore, recent studies have stressed the differential degree of these factors and the variability in adaptive strategies that developed across contemporary and past societies around the world (Degroot et al. 2022; Frankopan 2023; Hoyer et al. 2023). It is therefore important to underline how this paper focuses on a specific geographical area over a determined (albeit long) time span and aims to contribute to better disentangling the multitude of factors (such as climate change, economic and political strategies, change over time in global networks) that triggered archaeologically documented crises and regenerations.

The growing environmental data collected over the last two decades has mostly focused on the last glacial maximum and the following Holocene period on a global scale (Jones et al. 2019; Lawrence et al. 2021a; Walker et al. 2019). The detailed study of multiple samples gathered from different areas of the world, from Greenland (Rasmussen et al. 2007) to Turkey (Wright et al. 2015), to India (Dixit et al. 2014), and to the Mediterranean (Cook et al. 2016) allowed the identification of both changes at millennial scale (Jones et al. 2019) and a series of “abrupt” climate change events called rapid climate change, or RCCs. These occurred at different places, at different times, and with variable intensity. For example, the 9.3 ka BP RCC event represented a very dry period documented only in Greenland and Turkey, while the following 8.2 ka BP RCC event probably reached to central Asia, including the Indian subcontinent (Jones et al. 2019). Even the duration of these events was not uniform, as confirmed by the remarkable difference between the 5.2 ka BP and the 4.2 ka BP RCC events (Jones et al. 2019; Lawrence et al. 2021a). Yet, all the RCC events, including the most recent ones (Cook et al. 2015a), had an impact on past societies: the 4.2 ka BP RCC event is generally associated with the collapse of the Akkadian empire as well as many Bronze Age societies in Iran, the Levant, and Greece (Preston et al. 2015; Staubwasser and Weiss 2006; Weiss 2016; Weiss et al. 1993), while the 3.2 ka BP event, a dry period including drought episodes interspersed with decades of wetter climate and documented over most of Asia and Europe, has been considered a driver that triggered the end of Late Bronze societies in the Mediterranean and the Near East (Jones et al. 2019; Manning et al. 2023; Van De Mieroop 2008).

For the Near East, the reconstructions of long-term historical climatic trends rely on a variety of proxy datasets, such as pollen, foraminifera diatom and tephra records, and stable isotopes. However, the current dataset of climate proxy records is patchily distributed across the Near East, with the most significant concentrations in Anatolia, the Levantine region, the Caucasus, the Arabian Peninsula, and the Iranian Plateau. Central and southern Mesopotamia remain relatively under considered, although political stability in Iraq enabled fieldwork to be resumed, thus improving the number and quality of samples (Altaweel et al. 2019; Lippolis 2020; Marchetti et al. 2019; Marchetti and Zaina 2020; Rost and Di Michele 2022).

Based on these data, numerous studies have attempted to evaluate RCCs against known but still poorly understood historical events and sociopolitical trajectories. In particular, different datasets have already been tested in regions adjacent to southern and central Mesopotamia, such as in northern Mesopotamia (Clarke et al. 2016; Lawrence et al. 2021a, b; Palmisano et al. 2021b; Staubwasser and Weiss 2006) and in the Levant (Palmisano et al. 2019). These studies were useful to recognize RCCs among the drivers that contributed to triggering new sociopolitical scenarios as well as novel economic and urban strategies. For example, the 8.2 ka BP event had some impacts on the Neolithic societies of central Turkey at a local level (Roffet-Salque et al. 2018). On a larger scale, the 5.2 ka BP dry period has been connected with the decline of the Uruk expansion both in northern Mesopotamia and the Levant, being associated with a large-scale urban and demographic reduction (Bar-Matthews et al. 1999; Benati et al. 2021; Danti 2010; Palmisano et al. 2019; Parker et al. 2006; Riehl et al. 2009; Weiss 2000; Zanchetta et al. 2014).

Of great importance especially in northern Mesopotamia was the 4.2 ka BP event. Following the pioneering research by Weiss et al. (1993), the idea that this event, which lasted several centuries, could have strongly impacted the regions of the upper Khabur and beyond, contributing to the collapse of the Akkadian empire, has found further confirmation in other regions of the Near East (Kennedy 2016; Weiss 2016). However, a more widespread effect of the 4.2 ka BP event has been called into question (Danti 2010).

After a millennium, around 3.2 ka, another major RCC impacted a large region stretching from Anatolia to Iran, including the Levant and probably also the Greater Mesopotamian region (Jones et al. 2019). Drought is reported in Hittite texts (Kuzucuoğlu 2015) along with the destruction of the Hittite capital Hattusa (Manning et al. 2023), while in Syria and the northern Levant crop failures are documented (Kaniewski et al. 2010), together with massive destructions especially along the coast (Van De Mierop 2008).

Further RCC events like the 2 ka BP, one also had a substantial impact on different regions of the Near East (Jones et al. 2019), although, as with previous climatic events, as already stressed, not all societies were impacted in the same way. The current reconstruction of the effects of RCC events in the Near East provides much support for the interpretation of significant events of the past. However, there is still a macroscopic geographic gap corresponding to central and southern Mesopotamia, mainly caused by the lack of climatic proxies. To date, the only hints have been provided by studies that generally consider only a small sample of selected large polities (Benati and Guerriero 2021; Benati et al. 2021; Sanlaville 1989). Therefore, although data from northern Mesopotamia suggest that similar effects may have taken place to the south as well, the question of whether and how RCCs influenced settlement patterns in central and southern Mesopotamia remains an open one.

Computational Approaches

Over the last two decades, the growing public availability of geospatial sources and software has provided archaeologists with new tools to collect, analyze, and share data at an unprecedented scale (Bevan 2015; Hritz 2004; McCoy 2017; Ur 2006). By integrating the new tools with the data collected in the field, it has become possible to address what Kintigh et al. (2014) defined as the “grand challenges for archaeology.” According to McCoy (2017), these large-scale geospatial data, also defined as geospatial big data, should be organized by archaeologists in different ways, depending on the scope and the type of the available information. The Web GIS turned out to be an effective tool for visualizing, searching, processing, analyzing, and communicating archaeological data on the internet: the FloodPlains project (see below) represents an attempt at uniting these perspectives within an open-source architecture (hence financially sustainable prospectively), based on popular OS libraries (hence operationally sustainable prospectively). In a recent attempt at using artificial intelligence for the remote sensing of large areas, deep learning has been successfully tested in different contexts and with different methods; archaeological sites were singled out either by their elevation (in the Indus Valley; Orengo

et al. 2020) or their signature on satellite imagery (in southern Mesopotamia; Casini et al. 2023). The ability to model explanations of reconnaissance data is growing: the MASS (modeling ancient settlement systems) project pioneered this approach (Wilkinson et al. 2013), which is now slowly becoming mainstream (see below for demographic modeling).

Demographic Trends

Research on demographic trends at local, continental, and global scales over the past 40 years represents a key element in archaeological investigation aiming to understand processes underlying sociocultural change, as well as change in the interaction between humans and the environment, both at a contextual and cross-cultural level (Feinman 2011; Goldewijk et al. 2010; Reba et al. 2016; Shennan 2000, 2001; Stephens et al. 2019). Recent studies have focused on methodological developments linked to the reconstruction of demographic fluctuations in prehistoric continental Europe, the Mediterranean, and northern Africa, with particular emphasis on the impact of change on human interactions with paleoclimate, both at the level of subsistence strategies and culture (Berger et al. 2019; Fyfe et al. 2019; Manning and Timpson 2014; Palmisano et al. 2017, 2019, 2021a; b; Shennan et al. 2013; Timpson et al. 2014; Warden et al. 2017; Weiberg et al. 2019; Wigand and McCallum 2017). Although most of these methodological approaches concerning demographic estimates for the human past extracted information from large quantities of radiocarbon dates while dealing with their inherent uncertainty (Crema and Bevan 2021), a good amount of research, including studies centered on western Asian contexts, preferred to adopt a multiproxy approach comparing a variety of archaeological and paleoecological sources of information (Lawrence et al. 2021a; Palmisano et al. 2021b). However, while very informative and critical to infer potential processes of interest, the quantification of demographic trends using archaeological proxies (including ^{14}C dates) presents methodological problems and sets of theoretical assumptions that vary depending on the chosen variables.

All methods draw on the general assumption of a proportional relationship between the density of a given type of archaeological evidence, measured at the chosen temporal and spatial scale, and the (relative rather than absolute) intensity of human activity/occupation in the same study area at the chosen temporal resolution (Drennan et al. 2015). All archaeological variables, however, are inherently affected by taphonomic processes, loss of information with increasing temporal depth (Brantingham et al. 2007), biases in research design and intensity, resource biases, specific levels of uncertainty and error, potential temporal/spatial mismatch in their respective scale of analysis (French and Collins 2015; Müller and Diachenko 2019), uncertainty linked to modifiable archaeological units and processes of dispersal (Bevan and Crema 2020), and differences in scope and spatiotemporal sampling resolution (Perrault 2019), in addition to a number of often implicitly accepted assumptions such as that of uniformitarianism (French et al. 2021). Examples of adopted archaeological proxies include (but are not limited to) site counts, site size, stratigraphic information, genetic effective population size, bioarchaeological

demographic profiles (Bocquet-Appel 2002), carrying capacity, paleoenvironmental and paleoecological data, and summed probability distributions of radiocarbon dates (French and Collins 2015; French et al. 2021). For regional datasets mostly consisting of survey data, site counts and site extension are often readily available sources of information. Nevertheless, site count alone is particularly subject to research intensity biases, taphonomy, and chronological uncertainty due to surface findings, while the assumption of a linear relationship between settlement size and population density may or may not hold across periods or contexts (Palmisano et al. 2017).

For Mesopotamia, global demographic studies provided the earliest glimpses into long-term population trends by using estimates collected from different sources (Chandler 1987; Livi-Bacci 2007; Modelski 2003). However, despite the use of cleaning and harmonization approaches to make the data internally consistent (Reba et al. 2016), the reference datasets utilized, especially for the early periods, were far from being exhaustive. Projects such as HYDE (Goldewijk et al. 2010) and ArchaeoGlobe (Stephens et al. 2019) represented remarkable advances thanks to the collection of a large amount of data on urban density, population growth, cropland, and pasture extension over time. In the specific case of the ancient Mesopotamian floodplains, the limit of these studies, however, resided in the geographically and temporally coarse resolution of the final dataset (HYDE) and in the dramatic drop in the quality of the information collected for the last five millennia (ArchaeoGlobe).

Many recent works focusing on reconstructing demographic fluctuations in Near Eastern archaeological contexts used probabilistic approaches, namely aoristic approaches, aimed at explicitly addressing chronological uncertainty embedded in the chosen archaeological proxies, as well as at making different sources of information directly comparable at the chosen temporal resolution (e.g., Lawrence et al. 2021b; Palmisano et al. 2021b). This technique allows researchers to estimate the intensity of an event over time by standardizing the temporal units of analysis across the entire study period, and it has already been widely used on a broad range of archaeological contexts (see Bevan et al. 2013; Crema 2012; Johnson 2004; Orton et al. 2017; Palmisano et al. 2017; Ratcliffe 2000; Romandini et al. 2020). The approach draws on two main assumptions. The first one is that the total probability of observing the occupation of a given archaeological site in the temporal interval corresponding to a specific cultural phase is 1. In other words, we can be certain to see that particular site occupied in the archaeologically determined chronological interval. The second assumption, in the absence of better and more detailed information, is that of a uniform probability of existence/occupation of our site across the entire time interval of the cultural phase. This means that, if we divide the temporal length of our cultural phase into equal time blocks (e.g., 100-year bins), we end up having the same fraction of total probability of existence (otherwise named aoristic weight) at each time block. The relative aoristic weight would therefore depend on both the total temporal length of the cultural phase of interest and the width of each time block. If we perform the same operation across all sites, we can sum the aoristic weight of each site per each time block and obtain an aoristic sum that effectively produces a long-term time series with estimated intensity of site occupation over time. Although the method can be readily used and addresses some problems of uncertainty in the archaeological record, it is still prone to biases in the dating

precision of different cultural phases based on surface archaeological findings and on the life span of the most diagnostic artifacts for each cultural phase. These problems have to be addressed by further implementing Monte Carlo methods to simulate random start date and site duration based on theoretical or empirical prior probability distributions, and generate a probability envelope of existence based on the fact that the lifespan of most sites would be shorter than the entire duration of a cultural phase (Lawrence et al. 2021a, b; Palmisano et al. 2017).

Fieldwork

Archaeological fieldwork activities in Iraq largely came to a halt after the invasion of Kuwait in 1990 (although Iraqi-led research has taken place afterward). The political instability of the two following decades had a substantial impact on the advance of study of the central and southern Mesopotamia floodplain. Adams' dataset on the reconstruction of the ancient landscape was not updated until the early 2010s. Eventually, the slow resumption of archaeological excavations and survey projects over the last 15 years has allowed us to improve both the lists of archaeological sites and the geological and paleoenvironmental datasets, thus opening a new season for the study of the long-term settlement and demographic trends in the region. Table 1 shows an updated list of the surveys conducted up to 2022. The new millennium saw a resumption of work first in southwestern Iran and then in Iraq itself, which entailed an increase of the archaeological dataset therein, especially in terms of the quality of the data (Fig. 2; Table 1; Lippolis 2020; Maner et al. 2020; Marchetti et al. 2017, 2019, 2020; Marchetti and Zaina 2020; Otto et al. 2018).

The surveys were undertaken in different years by different teams (see Table 1), so one should expect a great variability in terms of precision and reliability of the ceramic indicators that were used for chronological determinations and also how they were collected on the ground, which can affect the results of subsequent research. However, as Brinkman (1984, p. 179) remarked: "It is easy to find faults in the methodology and conclusions of the surface survey, and the surveyors themselves have been the first to point this out and in frank detail. But we must resist the temptation to downgrade or dismiss the evidence."

(Re)investigating the Plains: An Updated Dataset and Fine-Tuned Approaches

Newly available archaeological datasets coupled with statistical methods for data analysis can be used to test and challenge the current paradigms and narratives on the long-term settlement and population trends in the southern Mesopotamian floodplains. We thus first collected all available archaeological evidence on the region in an online platform, which we called FloodPlains, a Web GIS developed between 2018 and 2021 at the University of Bologna, which includes all published archaeological sites in southern Mesopotamia (<https://floodplains.orientlab.net>). Our 4,941 entries consist of previously documented archaeological sites from 16 published

survey projects from the 1950s until today, which were manually identified one by one over satellite imagery (Fig. 1, Table 1). We addressed the three main research questions set out in the introduction by basing our analysis on 3,420 georeferenced archaeological sites collected in the FloodPlains Web GIS, for which we could take into account the estimated size for each occupation period, over a time span of more than 6,000 years.

Building the Dataset: The FloodPlains Web GIS

The construction of the dataset represented a complex task involving multiple steps as described in the previous sections. The brief description that follows of the software platform also aims at allowing the replicability and validation of our methodology and results (for an extended description see Marchetti et al. 2023). The development of the Web GIS entailed three main successive steps: data collection, data evaluation, and Web GIS implementation.

The first step was the collection of the geographical and archaeological data from the 16 archaeological survey projects carried out between the 1950s and 2020 (Table 1). We collected all the available open-access satellite imagery (i.e., Bing Maps Tile System, ESRI World Imagery, Declassified CORONA imagery) and topographic maps (OpenStreetMap, US Army maps from 1941–1942, and the *Atlas of Archaeological Sites of Iraq*, Baghdad 1976) of the Mesopotamian floodplain region to provide a solid geographical dataset. Published archaeological survey maps (Table 1) were then georeferenced within the UTM 38S Zone through the OS software QGIS 3.10, using open-access satellite imagery and topographic maps as reference points and producing shapefiles of the survey areas (Fig. 1). The positioning of surveyed archaeological sites was fixed by projecting them over the set of satellite imagery and topographic maps, which were carefully compared to obtain a precise shapefile of each site.

The second step consisted in filing the archaeological data produced by the 16 surveys in the southern Mesopotamian floodplains. Other survey projects were not considered (Al-Shukri 1974; Andrae 1903; Dougherty 1926) due to the impossibility of georeferencing their maps and the lack of chronological information for the sites. After a preliminary positioning of the sites, the possible shifts due to the limited accuracy of several pre-2000s archaeological maps in site location have been corrected using the satellite imagery archive in the geographical dataset. In total, 4,941 archaeological sites have been digitized, and a shapefile of the total area and an associated attribute table were produced. Among them, 3,420 also included information about chronology and area extension through time, while the remaining 1,521 correspond to archaeological sites identified by Adams (1965, 1981; Adams and Nissen 1972) but for which none of the above-mentioned information was provided. Another 2,964 records have been potentially identified as archaeological sites through remote sensing, but since they have not yet been checked through ground-truthing, they are not considered in the present paper, although they do appear in the Web GIS in a separate layer. In fact, it must be kept in mind that the different methodologies applied by the 16 survey projects considered in this research also

correspond to diverse data quality and results. Therefore, an essential step of our collection consisted in harmonizing the variety of information provided by each project without losing the level of detail provided. Consequently, in the Floodplains Web GIS, it is possible to find different degrees of detail in the attribute table of each archaeological site based on the survey project. Furthermore, a survey–resurvey approach (Banning 2002; Banning et al. 2017) was applied for some previously documented archaeological sites to validate their dimension, their chronology, the presence of structural features at each site as well as assessing current threats (Zaina 2019): 108 archaeological sites already identified in previous survey projects were thus visited again thanks to a collaborative approach of the QADIS, FARSUP, and MAITaB surveys.

The third step of the project was the implementation of the FloodPlains Web GIS for managing and researching georeferenced archaeological information. Its design and development rely on two key criteria: usability and openness to future developments. The web interface of FloodPlains is simple and easy to use. The visualization layout consists of a map with spatial information and a drop-down sidebar menu to manage the entire set of layers. The layers are organized according to two main types of data: archaeological and geographical. The group of archaeological layers named "Sites" is the result of the research performed by the different teams during data collection and data evaluation phases, and it is divided into "Survey" and "Remote Sensing." Both layers are linked to specific attribute tables.

FloodPlains is an open-source project, and its data and codes can be accessed at <https://github.com/bnza/archiraq>. This development strategy is integrated with our choices on the software division into layers, data normalization, use of standards for data transfer and of solid and popular frameworks, modularity of the software as well as intensive use of automated tests (both client and server side), and continuous integration automation (<https://travis-ci.org/github/bnza/archiraq>) to facilitate future developments of the system by the scholarly community.

Analysis of Estimated Diachronic Change in the Settled Area

To answer our first research question and make results directly comparable with the evidence available for nearby regions, we calculated a number of demographic proxies largely drawing on previous work by Palmisano et al. (2019). Our dataset used for the analysis consists of 9,695 site-phases (the current unit of observation) from 3,420 archaeological sites. To account for temporal uncertainty and potential biases due to differential research intensity, we adopted a probabilistic approach based on aoristic analysis (Bevan et al. 2013; Crema 2012; Johnson 2004; Orton et al. 2017; Palmisano et al. 2017; Ratcliffe 2000; Romandini et al. 2020). This approach consists of assigning a start and end date to each archaeological site-phase and dividing the entire temporal interval of the study period (in this case the period) into time bins of fixed width (100-year bins). The use of fixed temporal intervals is particularly advantageous as it allows for simpler comparisons between bin pairs. It will also make it possible to directly compare between estimated trends and additional proxies (such as climatic/environmental

ones) in future studies. Finally, a fixed temporal resolution is useful for a straightforward application of Laplace's principle of insufficient reason. Since, in this particular case, we lack any additional evidence for the exact intensity of occupation of each settlement during its lifespan (estimated archaeologically), we draw on Laplace's principle and use a uniform probability distribution as the best approximation of the process of interest, given our uncertainty as observers. This approach generates expected approximations, as the final probability of existence of a site-phase will be uniformly distributed across the time bins comprising its lifespan. Nevertheless, this represents the only solution not entailing the addition of independent evidence to the model and allows us to fully and explicitly embed our uncertainty in the obtained long-term pattern.

Based on the start and end dates of each site-phase, we divided the total probability mass of existence of each site-phase (equal to 1) across the t bins included in the temporal interval of the phase. The existence of each site-phase therefore presents with a uniform probability at each bin calculated as $1/t$. We then summed all the probabilities calculated for each site-phase falling in the same bin and repeated the same operation for the entire study period. The result is an estimate of the frequency distribution of site-phases for fixed and comparable time bins, which incorporates all the temporal uncertainty embedded in the data. We then calculated raw site counts proportional to 100-year bins, which we also multiplied by the minimum area of each site-phase. The obtained product was summed within each temporal bin to compute the regional total area (in ha) at the same chronological resolution as the other long-term trends.

Following the same steps, we calculated total aoristic sums and relative aoristic sums for each class of site size (Table 2). The latter were used to estimate diversity at each temporal bin through Hill's numbers (effective number of species) based on Simpson's concentration index to better control for the effect of rare classes (Hill 1973). Finally, following Lawrence et al. (2021a), we generated site counts with randomized start dates and durations. The former were drawn from a uniform distribution of dates constrained by the temporal limits of the site-phase of interest. The latter were then drawn from a normal distribution that assumed a mean occupation of 200 years and a 50-year standard deviation. We chose this duration time to favor comparability with previous studies, although this parameter is highly arbitrary, and regional empirical evidence should be further explored to obtain more grounded estimates. We adopted a Monte Carlo

Table 2 Archaeological sites ranking in southern Mesopotamia (according to Adams 1981, table 14).

Tier no.	Min (ha)	Max (ha)
6	200.1	-
5	40.1	200
4	20.1	40
3	10.1	20
2	4.1	10
1	0.1	4

approach and repeated this random sampling to obtain 95% confidence envelopes for estimated site counts to be compared with archaeological site counts.

Our main aims were to obtain a graphic representation of the temporal uncertainty linked to each cultural phase by observing the width of the envelope, to compare traditional measures (site counts) to measures of estimated intensity that more explicitly address temporal uncertainty, and to compare these long-term trends with diversity measures that may help us interpret the obtained time series in terms of settlement structure, i.e., if an increasing aoristic sum/site count corresponds to either a higher number of sites belonging to one or few classes (low diversity), or to a horizontal increase in all classes (high diversity), and scenarios in between.

Analysis of Population Trends

For addressing the second research question, we relied on Adams' (1981, table 14 and *passim*) six-tier classification of sites to analyze site rank development in our sample (Table 2). We made this selection for several reasons. First, the majority of archaeological sites in the area were documented by Adams (1965, 1981; Adams and Nissen 1972). The second reason is that Adams' tier system (1981, table 13, fig. 25) can be compared to philological studies (Steinkeller 2007, table 7 on the Umma region). In general, current narratives integrating archaeological and philological evidence agree on proposing ± 7 –9 ha as a meaningful threshold between villages and cities/towns (Algaze 2017; Pollock 1999; Steinkeller 2007; Wilkinson and Hritz 2013). The third reason is that this system has already been successfully tested by other studies on a smaller scale (Marchetti et al. 2019; Wilkinson and Hritz 2013). Therefore, we defined rural population living in sites of the lowest two tiers (0–10 ha) versus urban population inhabiting the sites in the other four tiers (>10 ha). This division provided the starting point for challenging the current interpretation of the demographic trends in southern Mesopotamia. While we cannot do justice here to the debate on population estimates in the Near East (e.g., Algaze 2008; Colantoni 2017; Postgate 1994; Wilkinson 2003; Wilkinson et al. 2013), by using the new FloodPlains dataset and a probabilistic aoristic approach on site size and chronology, we attempt to improve current narratives (Goldewijk et al. 2010; Stephens et al. 2019) and reconstruct the demographic trends from the late fifth millennium BC to the early second millennium AD in southern Mesopotamia. For each of the classes, we calculated aoristic weights to obtain a probabilistic weighted estimate of the number of settlements in each class to be used as a proxy for change over time of population size on the basis of the type of settlement.

The Relationship Between Demographic and Climatic Proxies

For the third research question, we selected published and available data on three geographically closest sources that yielded proxies of relative precipitation levels, i.e., stable oxygen isotope ratios ($\delta^{18}\text{O}$), on the basis of the assumption that in arid and semiarid contexts they are associated with available biomass and water (Jones

et al. 2019). This choice was also driven by the possibility to compare our results with previous works (Palmisano et al. 2021b).

Higher values of $\delta^{18}\text{O}$ suggest drier conditions, while lower values indicate a wetter climate, although other factors such as evaporation, vegetation, and air mass trajectories may also have an impact on this highly sensitive proxy, especially in Mediterranean and other semiarid contexts (Baker et al. 2019). The chosen proxies (Fig. 3) were obtained from three contexts: Kuna Ba cave speleothem (Longitude 45.64, Latitude 35.16; Sinha et al. 2019; Palmisano et al. 2021b), located at 660 m asl and covering a time span between 3988 cal yr BP and the present; sediment from Lake Zeribar (Longitude 46.11, Latitude 35.53; Palmisano et al. 2021b; Roberts et al. 2008; Stevens et al. 2006), located at 1300 m asl and covering between 20746 and 108 cal yr BP; and sediment from Lake Mirabad (Longitude 47.72, Latitude 33.08; Palmisano et al. 2021b; Roberts et al. 2008; Stevens et al. 2006), located at 800 m asl and covering between 9338 and 55 cal yr BP. While oxygen isotopes obtained from speleothems have been considered to be biased by winter precipitations rather than representing annual average values

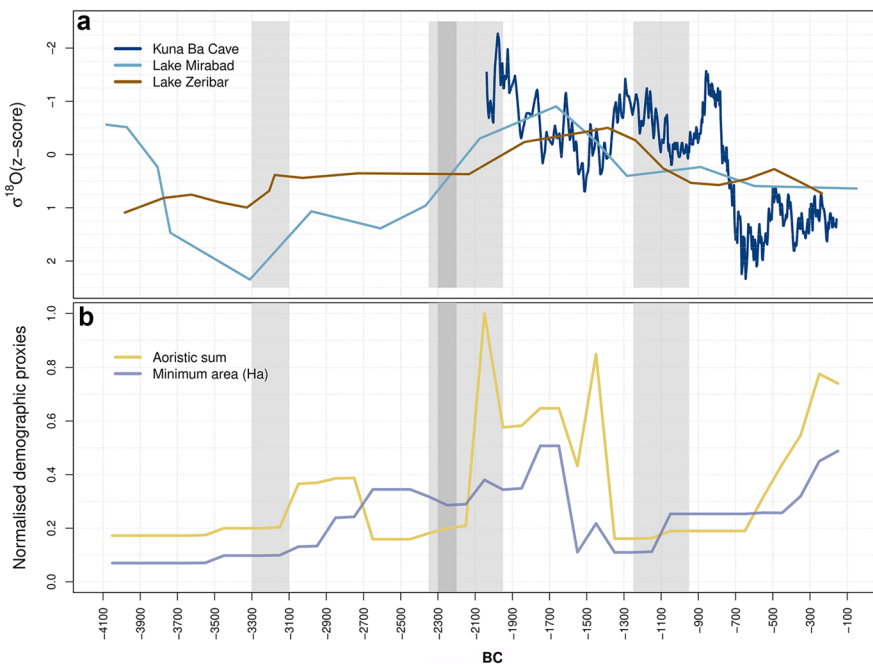


Fig. 3 Time series of the available proxies for the period 4100–100 BC: a) z-scores of proxies for surface water/biomass availability published in Palmisano et al. 2021a, b, calculated from the $\delta^{18}\text{O}$ isotope values from Kuna Ba Cave (Sinha et al. 2019), Lake Mirabad (Roberts et al. 2008; Stevens et al. 2006;), and Lake Zeribar (Roberts et al. 2008; Stevens et al. 2006;); b) aoristic estimate (yellow line) resulting from summing the probability of existence of all site-phases at each 100-year bin, and total regional minimum area (light blue), obtained by summing all the minimum areas of all sites counted per each 100-year time block

(e.g., Bini et al. 2019), the content of lacustrine carbonates may be in some cases associated with variability in summer rainfall levels (Bini et al. 2019; Palmisano et al. 2021b; Zielhofer et al. 2019).

While Kuna Ba cave presents finer chronological detail that allowed us to directly compare its oxygen isotopic values with the present paleodemographic proxies by binning it into 100-year time slices (for the period 2038–253 BC), the remaining two samples exhibit a mean sampling interval greater than 100 years, i.e., the temporal bin size chosen for our aoristic analysis of settlement counts and estimated area. Following Palmisano et al. (2021a, b), we therefore selected the respective temporal intervals in which both settlement estimates and paleoclimatic proxies overlapped, i.e., the period 4000–200 BC for Zeribar Lake and the period 4100–100 BC for Mirabad Lake. We then binned climatic data (i.e., the respective z-scores following Palmisano et al. 2021b) and settlement proxies into 500-year intervals (Fig. 4). We finally obtained a global correlation value for each sampled location. Considering the small size of binned samples for Zeribar ($n = 8$) and Mirabad ($n = 9$), we used the non-parametric Spearman's correlation

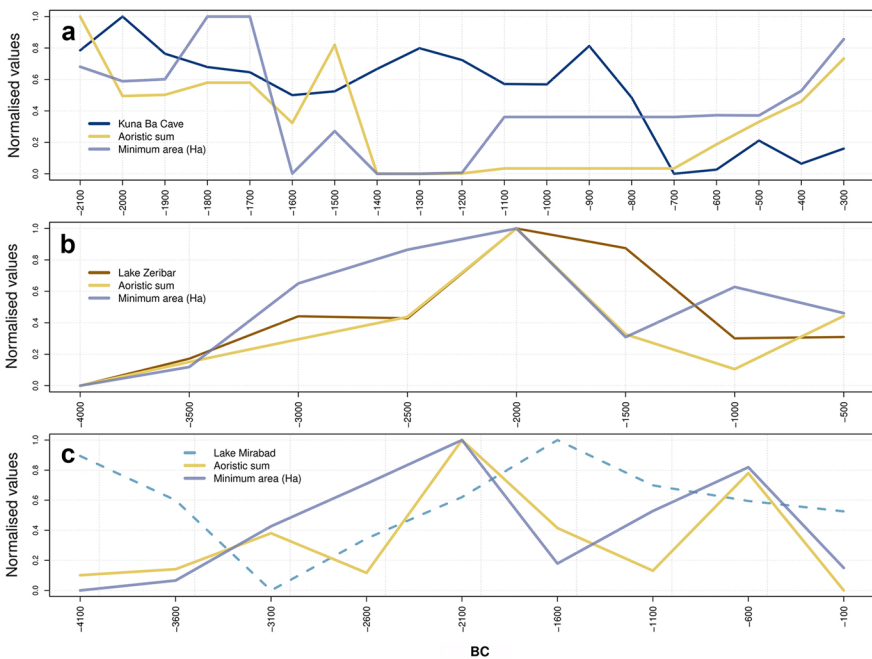


Fig. 4 Normalized averaged values for each palaeoenvironmental proxy and comparison with demographic proxies summed using the same temporal binning (aoristic sums and total regional minimum area, respectively): a) z-scores for $\delta^{18}\text{O}$ obtained from Kuna Ba Cave between 2100 and 300 BC averaged using 100-year bins; b) z-scores for $\delta^{18}\text{O}$ obtained from Lake Zeribar between 4000 and 500 BC averaged using 500-year bins; c) z-scores for $\delta^{18}\text{O}$ obtained from Lake Mirabad between 4100 and 100 BC averaged using 500-year bins

coefficient in these cases, while we opted for Kendall's Tau in the case of Kuna Ba cave, given the additional lack of linear relationship between variables.

We chose not to implement a moving window approach given the narrow chronological span covered by each climatic proxy and the wide time slices imposed by their mean sampling interval. Rainfall trends were compared against both aoristic sums and estimates of minimum cumulative area per temporal bin.

Building the Plains: New Light on Long-Term Urban Trajectories

We used a probabilistic approach (Fig. 5) to measure variation over time in demographic proxies such as the number of sites, aoristic sums, absolute and relative estimates of aoristic weight per each size class (Table 2), and minimum total (regional) area. All proxies were measured in 100-year temporal bins to facilitate cross comparisons. Figure 5a–c shows the results of the urban trend analysis normalized between 0 and 1. Although the analysis shows that a gradual growth in the number of settlements and the urbanized area started in the course of the fourth millennium BC, since 3100 BC and through the first centuries of the third millennium, there was a substantial increase (Fig. 5b); this first cycle of urban growth lasted for approximately 400 years, then ended abruptly around 2700 BC. This cycle is relevant in that it triggered a long-term decrease in class 1 settlements (up to 4 ha), which reached their minimum around 2200 BC (Fig. 5c; 0.6), and a corresponding increase of all the other classes, in particular 2 (4–10 ha) and 3 (10–20 ha). During the inter-cycle phase (2700–2200 BC), the overall number of sites remained somewhat steady (Fig. 5a), while both the urbanized area and the diversity of classes increased (Fig. 5b). The latter trend can be explained by the substantial drop of class 1 sites in favor of both intermediate (class 3) as well as emerging megacities (class 6).

Between the end of the third millennium BC (around 2200 BC) and the mid-second millennium BC, we observe a second longer urban cycle (Fig. 5a). This new phase is characterized by a sharp increase in the number of settlements that, however, does not correspond to an equally distinctive increase in settled area (Fig. 5b). This paradox is explained by the effective number of classes, showing an increase in diversity. In general, this second cycle highlights a more complex and diversified trend than the previous one. Both the number of sites and the overall urbanized area experienced numerous fluctuations, while the trend of size classes was more stable. Compared to the urban experiments of the first cycle and the inter-cycle phase, after 2200 BC, there was a new net increase of class 1 sites. This datum confirms the return to a distribution of minor settlements over a larger area and a partial depopulation of large centers, in particular class 6 megasites.

The beginning of the Late Bronze Age, around the mid-second millennium BC, marks the onset of a second inter-cycle period that lasted almost a millennium through most of the Iron age (1600/1400–700 BC) and was characterized by a substantial drop in the number of sites and in overall settled area (Fig. 5a, b). This trend is comparable to the first inter-cycle period. Then from about 1100 BC onward, the overall urbanized area slowly grew again. The variation in settled area corresponds

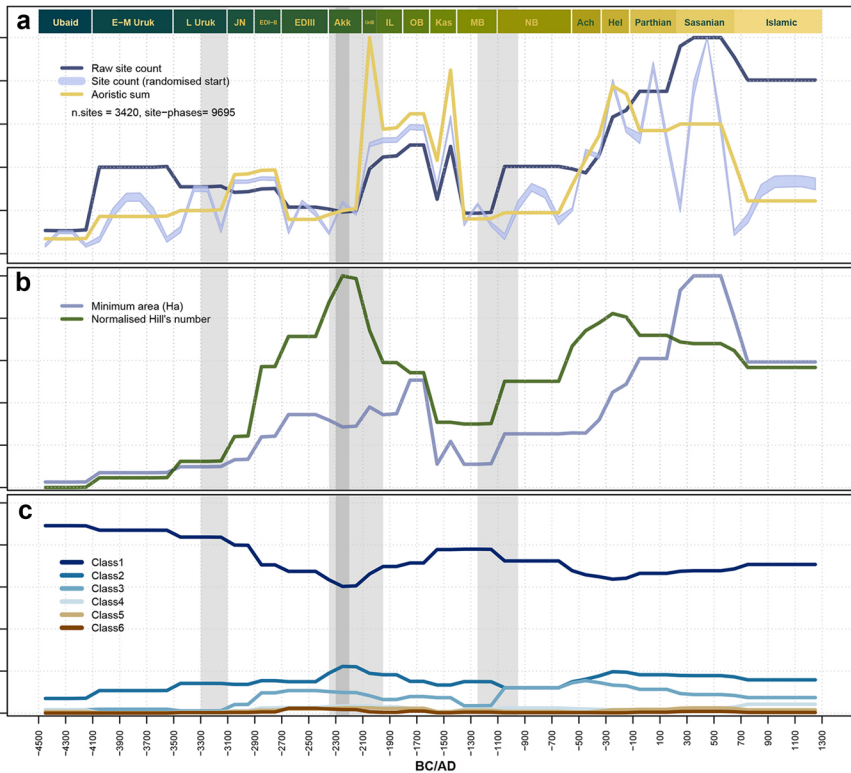


Fig. 5 Diachronic change in the southern Mesopotamian floodplains. All figures report long-term diachronic trends, which were normalized to unit for making them directly comparable to each other. The uppermost panel (a) shows three different proxies for population trends based on the number of archaeological features documented at fixed temporal intervals (i.e., 100-year time bins): raw site counts made proportional to 100-year time blocks (dark blue); an envelope representing the 95% confidence interval obtained by simulating site counts with randomized start dates, assuming an average occupation of 200 years (light blue); an aoristic estimate (yellow line) resulting from summing the probability of existence of all site-phases at each 100-year bin. This is obtained by dividing the total probability of existence of each site-phase for the number of time blocks included within its start and end dates. The central panel (b) shows the total regional minimum area (light blue), obtained by summing all the minimum areas of all sites counted per each 100-year time block, and the Hill's number (effective number of species, green line) based on Simpson's concentration index. The latter was calculated on the relative aoristic weight of each site size class (bottom panel, c, see Table 2) and indicates if each time bin is more or less homogeneous on the basis of the relative number of small, medium, and large sites

to a new partial reduction of class 1 sites, counterbalanced by increases of class 3 and 4 site, indicating a shift of the population toward larger centers (Fig. 5c).

Between 700 and 600 BC, a third urban cycle began, which lasted for about 1300 years. Both the number of sites and the urbanized area reached an unprecedented extension, with the sharp increase in the settled area leveling off only at the end of the cycle, corresponding to the end of the Sasanian empire in the course of the mid-seventh century AD (Fig. 5a, b). However, these patterns did not have significant effects on the overall relationship between large urban centers, medium-sized

towns, and rural villages and hamlets (Fig. 5c). Indeed, the overall class ratio followed the second inter-cycle trend. The albeit limited fluctuation only suggests a gradual increase of both class 1 rural villages and class 6 megacities to the detriment of intermediate centers. The end of the third cycle brought a substantial reduction of both the number of settlements and the overall urbanized area that characterized the following inter-cycle phase (Fig. 5a–c).

Living the Plains: A Fine-Tuned Perspective on Long-Term Population Trends

Comparing the obtained paleodemographic trends and the three selected sets of paleoclimatic evidence does not highlight consistent feedback across different proxies. Values obtained from the Kuna Ba cave for the period 2038–253 BC, for example, are substantially uncorrelated (despite the negative sign) with either aoristic sums ($\tau = -0.04$, $p = 0.8$) or estimated total inhabited area ($\tau = -0.04$, $p = 0.8$). Data from Lake Mirabad present only a small positive correlation with aoristic sums ($\rho = 0.13$, $p = 0.74$) and a small negative correlation with summed settlement area ($\rho = -0.25$, $p = 0.52$). On the contrary, long-term and coarse patterns exhibited by oxygen isotopes from Lake Zeribar strongly and positively correlate with both aoristic sums ($\rho = 0.76$, $p = 0.04$) and estimated settlement area ($\rho = 0.71$, $p = 0.06$). Results obtained here for southern Mesopotamia are limited by the coarse scale of the available proxies and the short temporal intervals they cover. Nevertheless, they seem to support previous results obtained for northern Mesopotamia, which suggest increasing independence between demography and water/biomass availability from the second half of the middle Holocene onward (Palmisano et al. 2021b). At the same time, coarser trends offered by Lake Zeribar hint at a potential impact of the 4.2 cal yr BP event on demographic pressure in the region of interest by means of a strong and positive relationship. The approach presented here provides for the first time the opportunity to further examine the outlined trends by using the most updated dataset, which allows us to appreciate the three urban cycles observed across the six settlement size classes (Table 2).

While class 1 and 2 sites show substantial demographic growth from the early fourth millennium BC, the onset of the first cycle in all the other classes began around 3100 BC and continued through the third millennium BC. At that time, the Mesopotamian population appears to have been quite evenly distributed in all the classes, although the majority still inhabited class 1 settlements. This pattern confirms at regional level what has been already observed at a local scale (Marchetti et al. 2019) and suggests that toward the turn of the millennium there was an unprecedented gradual shift from small rural villages to medium and large-scale urban sites located along the main watercourses. This evidence is corroborated by the observation that during the second part of this first cycle, corresponding to the Early Dynastic I period (2900–2700 BC), a substantial population increase occurred. Indeed, the inhabitants of class 3 to 6 settlements (medium and large-scale urban sites) doubled, while the population of class 1 sites remained somewhat stable.

The second cycle offers a more complex picture mirroring the new results of the analysis of urban trends. In particular, the two main population peaks are confirmed during the Ur III period (2100–2000 BC) and around the mid-second millennium BC, just before the dramatic settlement drop that sparked the second urban inter-cycle period (see above). This trend is particularly apparent for smaller centers (classes 1 to 3), while a more nuanced trajectory is observed for classes 4 and 5. It is noteworthy how medium-size sites ranging from 20 to 40 ha (class 4) were less subject than all the others to significant variations in both the number of sites (Fig. 5c) and the size of the population (Fig. 6), a trend rarely repeated in other periods. Class 5 sites played a major role during the first part of the second cycle, with their population during 2100–2000 BC attested somewhere between 150,000 and more than 300,000.

The demographic dynamics of the second inter-cycle is comparable to the first one. The only event that catches the eye was a modest but relevant population increase in small centers (classes 1 and 3), which occurred around 1100 BC.

The third cycle (Fig. 6) is the longest and shows a quite uniform trend in all the classes apart from class 4. The onset of this new cycle seems to have been sparked by the gradual increase from 600 to 500 BC onward of population mostly in class 1, 2, 5, and 6 sites. The first part of this cycle shows a substantial population increase reaching its peak during the Hellenistic period (around 300 BC), which then became stable until the emergence of the Parthian empire. Then, during the second part of this cycle, we observe another significant population growth especially in the urban centers exceeding 40 ha (classes 5 and 6).

This trend lasted until the end of the Sasanian period (AD 650) and brought the overall population of the Mesopotamian floodplains to an unprecedented level. The transition from the Sasanian to the Early Islamic rule over the region corresponds to a new population drop, which characterized the last centuries of the first millennium AD and the beginning of the second millennium AD.

Reconstructing the Plains: Discussion

The systematic analysis of surveyed sites provided us with a fine-tuned picture of settlement patterns and population trends in southern Mesopotamia between the late fifth millennium BC and the early second millennium AD. The emerging picture is characterized by different macro-cycles of boom and bust in urbanization and population trends of different durations. To provide an interpretation as comprehensive as possible for this reconstruction, we integrated in our discussion, inasmuch as possible, the paleodemographic trends versus the selected paleoclimatic proxies with their RCCs (see above) as an additional variable to understand macro-cycles (Jones et al. 2019; Thompson and Zakhirova 2021, table 2.1). As already noted above, this endeavor is limited by the fact that, on the one hand, paleoclimatic research for southern Mesopotamia is sketchier than for neighboring areas, mainly due to the standstill of fieldwork there after 1990 (Jones et al. 2019; Lawrence et al. 2021a, b). What we propose here are, in fact, a series of possible mechanisms related to the trends highlighted in our research, taking into account current methodological

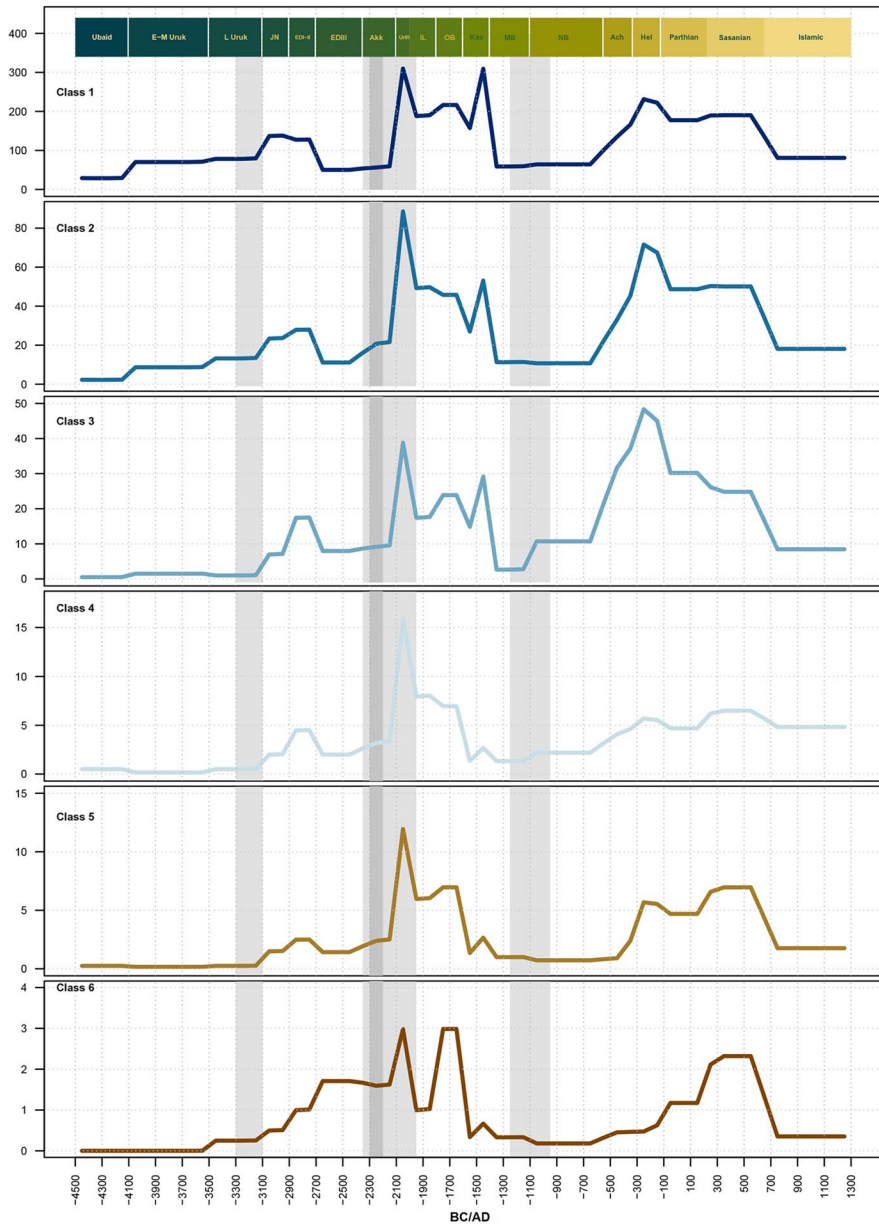


Fig. 6 Absolute aoristic weights calculated for each settlement size class (from class 1 to 6, see Table 2), showing the different trends over time obtained for small, medium, and large sites identified in the study area. The different scale reported for each class is informative on their relative weight on the total estimated counts. Gray bars indicate the three major arid events discussed in the text (i.e., the 5.2, 4.2 and 3.2 ka BP events)

constraints, including the use of different chronological systems as well as the level of detail and the field results by the various surveys. On the other hand, it is critical to stress that paleoenvironment is but one of the many, intertwined factors concurring to ignite and fuel change over time in human settlement strategies. Socioeconomic variables, political decisions, and the emergent properties of interaction and trade networks should also be considered to get a more complete and nuanced picture of these complex adaptive mechanisms: different sets of variables lead to differential responses and outcomes (Hoyer et al. 2023).

Keeping in mind these limitations that still hinder our ability to fully disentangle correlation and causation in the interactions between humans and their environment, our attempt opens some new research avenues on a thematic area that is still under investigated. Below, we try to reconstruct demographic fluctuations from a quantitative point of view, also assessing them qualitatively against climate trends whenever possible (the three major events are also detectable in Figs. 3 and 4). Our dataset has, furthermore, been designed to be fully integrated and compared with others from northern Mesopotamia and the Levant (Benati et al. 2021; Lawrence et al. 2021a).

The Late Chalcolithic Formative Phase (4300–3100 BC)

The data relating to the late fifth and the fourth millennium BC are consistent with previous narratives, indicating, besides sites such as Uruk, Ur and Eridu (Ur 2013; Wright 1981), a preponderance of small centers (classes 1 and 2) scattered throughout the territory (Adams 1981; Ur 2013). Climate change events may have certainly played a role in shaping and influencing the settlement and demographic patterns of this period: the still limited data suggest fluctuations from 5.9 ka BP onward (Jones et al. 2019; Lawrence et al. 2021a, b; Thompson and Zakhirova 2021) that may have triggered, as a response mechanism, the improvement of irrigation techniques (now focusing on small distributary fans or crevasse splays, Wilkinson 2003) to ensure food supply, in addition to the role played by the evolving ancient coastline (Aqrawi 2001; Kennett and Kennett 2006).

This situation required a complex and widespread labor organization, the establishment of new settlements, and the shift of decision-making power from landholding households or kinship groups to larger entities, such as temple estates, better capable of managing the changing landscape (Benati and Guerriero 2021; Renger 1995; Rost 2015). However, it has been pointed out (Rost 2017) that this shift from small to larger ruling entities occurred rather slowly and with possible geographic differences.

First Cycle (3100–2700 BC)

Previous narratives on the fourth to third millennium BC transition did not address the potential role of RCCs in influencing sociopolitical strategies of southern Mesopotamian societies. Our data show that since 3100 BC the processes that had already started during the middle centuries of the fourth millennium BC received a strong

impulse that led to a settlement and population boom and an increase in large-scale cities. This can be associated with the emergence of a more formalized water management system (Rost 2017; Wilkinson 2003). Long-term climate fluctuations of the fourth millennium BC reached their peak with the 5.2 ka BP event (Clarke et al. 2016; Danti 2010; Jones et al. 2019; Palmisano et al. 2021b; Riehl et al. 2009; Staubwasser and Weiss 2006).

The response to the 5.2 ka BP arid event, with the resulting urban and demographic patterns that emerged, focused on the optimization of the hydraulic landscape benefiting also transport and trade (Benati and Guerriero 2021; Benati et al. 2021). To achieve that, the administrative elites attracted/coerced part of the rural population into sprawling urban centers (e.g., Adab, Nippur, Lagash, Ur, etc.), aiming to acquire the larger number of laborers required for the construction of new water infrastructures (chiefly harbors, canals, embankments, and basins) for controlling seasonal flooding, enabling navigation, and optimizing water management for irrigation in an initially arid environment (Renger 1995; Rost 2015). This also resulted in time in an articulated network of settlements that were located along both the main courses of the Tigris and Euphrates as well as the new artificial canals and probably depended on the incrementally more efficient water management (started during the previous arid phase). In southern Mesopotamia, during the early third millennium BC, urban population equaled the rural population (Marchetti et al. 2019). From an economic perspective these mechanisms gave rise to regulated inter-city economic cooperation, documented by the so-called city seals (Matthews and Richardson 2018), leaving open the possibility of a regional coordination exerted by Uruk (Marchesi and Marchetti 2011), which furthermore equipped itself with a military infrastructure (Nissen 1972).

Inter-Cycle Period (2700–2200 BC)

Previous narratives recognized the middle centuries of the third millennium BC as the period of the emergence of the so-called Sumerian city-states, followed by the establishment of the Akkadian empire, i.e., one of the apexes of urban nucleation in southern Mesopotamia (Adams 1981; Ur 2013). Our data suggest a trend of settlement nucleation characterized by the continuing decrease of the smaller centers counterbalanced by an increase of the larger ones, thereby suggesting a continuing shift of the overall population toward the latter and along the main watercourses.

Accordingly, we observe how the process, started during the first cycle, reached its maturity: next to the well-defined urban layout of the larger centers (Liverani 2013) and the more widespread organization of irrigation systems and harbors (Rost 2017), an accrued state of warfare entailed the strengthening of the royal figure and the fashioning of the administrative elites into palatial courts (Marchesi and Marchetti 2011), as well as the establishment of conscripted armies (Benati and Guerriero 2021). Later Early Dynastic rulers and then the Akkadian kings further diversified the economy by intensifying predatory wars and long-distance trade via the Euphrates and Gulf routes (Benati et al. 2021; Massa and Palmisano 2018).

This positive trend ended quite abruptly around 2200 BC, due to different inter-related factors, chiefly an enduring state of warfare ultimately entailing a fall in the levels of trade at the same time of a major disruptive climatic event at 4.2 ka BP (Riehl 2014), which is well documented in northern Mesopotamia and the Levant (Lawrence et al. 2021b; Palmisano et al. 2021b; Weiss 2017).

Second Cycle (2200–1500 BC)

Previous narratives recognized a long and complex political period characterized by the embattled supremacy and final demise of large political entities including the Third Dynasty of Ur and the dynasties of Isin, Larsa, and Babylon (Liverani 2013). As in the case of the first macro-cycle, the second one is probably the result of a process of adaptation to the second climatic event of 4.2 ka BP. The connection between the changes in the settlement and demographic trends that occurred during this cycle and the climate fluctuation connected to the 4.2 ka BP event are also supported by the positive relationship between the demographic and climate proxies from Lake Zeribar (particularly relevant for the summer season).

Our data confirm a return to a settlement strategy characterized by numerous smaller centers with a capillary distribution throughout the landscape and a carefully planned (re)foundation of large cities (Wilkinson and Hritz 2013). The response mechanisms that brought to the adaptation and reorganization of southern Mesopotamian societies benefited from the previously achieved greater ability to control and manage the watercourses for navigation and irrigation (Rost 2017), with far-flung trade networks that got a new boost at the end of the third millennium BC (Benati et al. 2021; Massa and Palmisano 2018).

Therefore, to avoid new sociopolitical shocks caused by endogenous (conflicts) and/or exogenous (climate change) factors, we believe that the emerging political entities reorganized economic and institutional management models and promoted a more widespread presence on the territory of both workers and state employees (Rost 2017) to guarantee control over agricultural production and breeding. As a result, former major centers experienced a remarkable depopulation in favor of newly funded villages and hamlets and a more extended web of waterways to connect them (Rost 2015, 2017).

Inter-Cycle (1500–650 BC)

Our data on the second long inter-cycle period show an overall drop in the number of settlements (especially the smallest ones), with population trends paralleling those of the first inter-cycle period. The factors contributing to the occurrence of this event are numerous. According to Liverani (2013), a general social and political crisis, consisting for example in exogenous invasions or regional warfare, affected most of the Mesopotamian region between the second half of the second millennium BC and the beginning of the first millennium BC. Moreover, Kaniewski et al. (2013) stressed the relevance of a 3.2 ka BP environmental event as another major variable to be considered.

However, diverse regional responses to these factors took place in the Near East: in the Levant and in northern Mesopotamia, there was a significant demographic boom, in Anatolia the situation remained somewhat stable, while in the Arabian Peninsula and the Caucasus there was a limited population increase (Lawrence et al. 2021b; Palmisano et al. 2021b). Our data show instead that the southern Mesopotamian population responded to this new climatic event in a different way compared with the previous ones: in fact, while the 5.2 and 4.2 ka BP events seem to have been among the main driving forces for social, political, and economic changes, the response to the 3.2 ka BP aridification in lower Mesopotamia was limited to a slow increase in the intermediate centers to the detriment of smaller ones, something that would have gone along with the reorganization of cultivated areas. This interpretation can be also supported by the recent analysis of the 3.2 ka BP event in Anatolia (Manning et al. 2023), compared with the simulation carried out for a later period by the Old World Drought Atlas team (Cook et al. 2015b). However, this hypothesis certainly needs more detailed studies, as most of the relevant data remain unpublished, thus making current narratives preliminary at best (Bagg 2012; Rost 2017; Sinha et al. 2019).

Third Cycle (650 BC–AD 650)

A more localized but disruptive climate event seems to have taken place at the end of the second inter-cycle in northern Mesopotamia beginning at the end of the eighth century BC, which contributed to the crisis of the Neo-Assyrian empire (Sinha et al. 2019), although its effects in southern Mesopotamia cannot yet be assessed. The emergence of the Achaemenid and the following Parthian and Sasanian empires substantially opened the Near East to wider organizational dynamics, bringing new religious and sociopolitical structures (Liverani 2013). We observe an unprecedented increase of all the classes of settlements reflecting an urban and demographic boom, which lasted until the fall of the Sasanian empire.

Our data point to a first phase characterized by a vigorous increase of small centers that reflects the territorial control and management systems of the area established in the Neo-Babylonian, Achaemenid, and Hellenistic periods (Adams 1981). This trend continued also under the Parthian rule, although already during the first century AD, exogenous military pressures both in northern and in southern Mesopotamia probably led to the abandonment of numerous villages and hamlets in favor of larger centers. This second urban and population trend of the cycle reached maturity during the Sasanian period. Indeed, since the third century AD onward a major centralization of administrative and fiscal processes together with a renewed organization of the agrarian landscape was undertaken, including gigantic hydraulic works (Adams 1981, 218), possibly in partial response to other climate fluctuations that occurred during the fifth century AD (Thompson and Zakhirova 2021, table 2.1, no. 7).

Inter-Cycle (AD 650–1250)

Our analysis shows that the onset of the Early Islamic rule over much of the Near East in the mid-seventh century AD had consequences for southern Mesopotamia, too, in terms of settlement patterns as well as population trends. Indeed, the substantial drop of the urbanized area and the demographic decrease that affected all the site classes suggests a new inter-cycle period (see also Thompson and Zakhirova 2021, table 6.2 for external reasons, such as plagues, compounding this trend and table 6.3 for the sharp decline in Mesopotamian tax assessments). This reduction is less apparent among small centers (class 1), thus suggesting a settlement strategy characterized by numerous scattered villages and hamlets and few major centers (like Baghdad, Karbala, Kufa, or Basra) along the main watercourses. Adams (1981) and others (Altaweel et al. 2019; Campopiano 2017) interpret this change with the overall different political and economic strategy in the transition from the Sasanian to the Abbasid rule. Moreover, there is a growing consensus (Altaweel et al. 2019; Hoyer et al. 2023) around the fact that frequent alternating events of high rainfall and very dry years during this period could have had an important role in reshaping settlement strategies and population trends. According to Campopiano (2017), a substantial contribution was the socioeconomic and institutional changes that occurred over the country: in particular, the institutional changes favored tax-farmers and merchant-bankers, which led to irrigation policies bent to the interests of these new groups, often laying in short-term gains rather than in long-term success, and in the long run, this led to the breakdown of the agricultural system in ancient Iraq.

Concluding Remarks and Future Outlooks

Our study has provided a comprehensive picture of the long-term urban and population trends in southern Mesopotamia between the Late Chalcolithic 1 (c. 4300 BC) and the end of the Early Islamic period (c. AD 1250). The results allowed us to contribute some answers to the research questions underpinning our research. In particular, we have found that there are negative and positive relationships that have been qualitatively assessed by comparing paleodemographic and climatic data. The observed relationship of demographic and climatic proxies has also made it possible to support, especially for the most ancient phases, the hypothesis of a possible influence of some climatic events on settlement strategies and population dynamics, despite an increasing decoupling between population trends and surface water/biomass availability especially during the Iron Age (Palmisano et al. 2021b). As a result, the climate events of 5.2, 4.2, and 3.2 ka BP may have contributed to the three urban and demographic cycles in southern Mesopotamia.

We also outlined specific settlement strategies corresponding to each event, as regards the size and distribution of the inhabited centers (nucleation or dispersal may also be seen as adaptive strategies). The urbanization process is thought to have started a decoupling between RCCs and settlement trends enabling quick adaptive strategies to environmental changes (Lawrence et al. 2021b), but our study,

especially for the early phases, highlighted booms and busts also with possible causal links between human population and climatic changes. This is in line with the concept of polycrisis, which stresses the importance of integrating multiple often interrelated factors to grapple with the complex dynamics that can lead to the collapse and regeneration of contemporary and past societies (Hoyer et al. 2023).

More archaeological and environmental data will be needed to examine the respective feedback between climate, environment, and human population, but we are confident that the FloodPlains dataset will provide a significant tool for future comparative studies. In particular, the methodology used here and the results produced will allow future studies to compare the results of this research with the trends already highlighted for northern Mesopotamia (Palmisano et al. 2021b). This will eventually provide a comprehensive reconstruction of the long-term urban and demographic trends both in northern and in southern Mesopotamia over the last 6000 years.

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Declarations

Competing interests The authors declare that there are no other competing interests.

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