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Early urbanism in Mesopotamia coincided with increased moisture between 6500 to 5500 years BP

Mark Altaweel [a,*], Diary Ali Mohammed Amin Al-Manmi [b], Andrea Squitieri [c], Alice R. Paine [d], Karen Radner [e], Dominik Fleitmann [d]

[a] University College London, Institute of Archaeology, London, WC1H 0PY, UK
[b] Sulaimani Polytechnic University, Wrme Street 327-76 ,Qrga, Sulaymaniyah 70-236, IQ, Iraq
[c] University of Padova, Department of Cultural Heritage, Piazza Capitaniato 7, 35139 Padova, IT, Italy
[d] University of Basel, Department of Environmental Sciences, Basel, 4056, CHE, Switzerland
[e] Ludwig-Maximilians-University of Munich, History Department, Schellingstrasse 12, Munich, DE, Germany

A R T I C L E I N F O

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A B S T R A C T

Climate change is thought to have played a significant role in the rise and demise of complex Mesopotamian societies throughout the mid- to late Holocene. However, assessing the links between societal change and climate variability has been historically challenging, in part due to an absence of long-term, well-dated palaeoclimate archives located in close proximity to key archaeological sites. Here, we synthesise proxy data with archaeological information from Mesopotamia to demonstrate that the earliest urban development documented in this region coincides with increasing and potentially peak effective moisture in the mid-Holocene by ~5500 BP. We posit that increasing moisture availability likely facilitated the expansion and development of the earliest cities, with resource extraction under favourable climatic conditions providing new opportunities for urban centres to expand their resource areas into new domains, and far beyond what is evident in earlier periods. Following ~5200 BP, these same archives show increasing aridity coincident with the end of the Late Chalcolithic, and abandonment of several key settlements. Taken together, our work contextualises the evolution of critical urban centres in Mesopotamia between 6500 to 5500 yrs BP, and underscores the sensitivity of these centres to climatological variability.

1. Introduction

The development of urban centres in Northern and Southern Mesopotamia, between ca. 6500 to 5200 years before present (hereafter BP; from 1950), represents a watershed moment in the history of complex societies. Not only in Mesopotamia, but also in the broader history of complex societies. The earliest Mesopotamian settlements are considered some of the clearest examples of the transition from village to urban life, characterised by extensive urban population growth, the development of writing and large-scale political administration, and the rise of social complexity defined as societies with high organisation, interconnected systems, and evident specialisation (Algaze, 2008; Ross and Steadman, 2017). However, despite its importance, less clear is the extent to which this transition is influenced by regional climatological factors.

Uncertainties surrounding the importance of climate for urban societal development in Mesopotamia stem in part from the lack of high-resolution, sufficiently resolved palaeoclimate data from archives located at the core of the region. The socio-environmental context of urbanisation in Mesopotamia during the mid-Holocene has typically been explored using more distal archives, sourced from the Mesopotamian borderlands. On the one hand, certain records suggest that urbanisation developed during the so-called Mid-Holocene Climatic Transition, under a drier and more arid climate (Brooks, 2012; Clarke et al., 2016). Others suggest either that humid conditions peaked prior to the development of urbanism (Lawrence et al., 2022), or that this development occurred during the so-called Mid-Holocene Climate Optimum, where warm and humid conditions became conducive for settlement (Engel and Brückner, 2021). This discrepancy can (at least in part) be explained by the fact that most palaeoclimate records used in this context, including cave speleothem data, have derived from the Levant (Bar-Matthews et al., 2003; Verheyden et al., 2008; Cheng et al., 2015) and/or Anatolia (Roberts et al., 2011). However, recent historical climate and future climate projections show considerable variation in rainfall across the Middle East, such that parts of Mesopotamia often

* Corresponding author.
E-mail address: m.altaweel@ucl.ac.uk (M. Altaweel).

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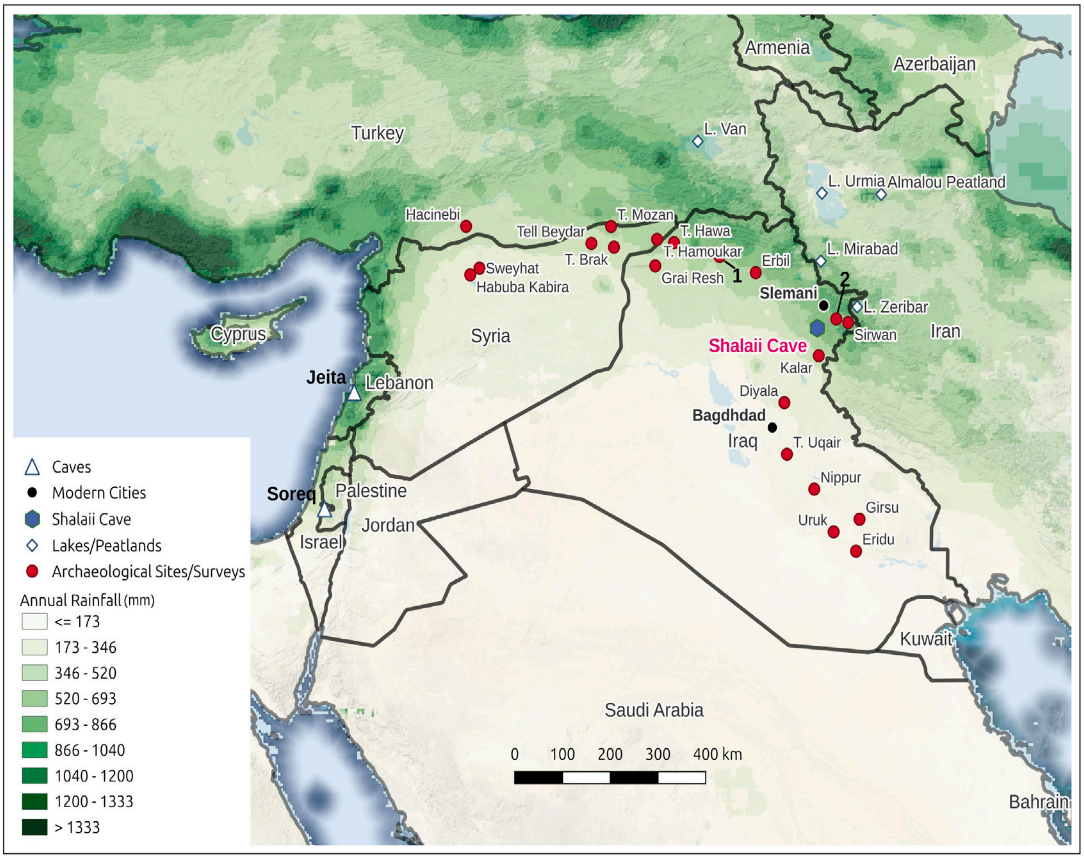

Fig. 1. Map of Mesopotamia featuring key archaeological sites and sample areas mentioned in the text. Items '1' and '2' are Tepe Gawra and Shahrizor, respectively. The abbreviations 'T.' and 'L.' represent the words 'Tell/Tepe' and 'Lake' respectively. Rainfall data are after CHIRPS (2025) and shown as discrete interpolated values with continuous display using regional data.

experience distinctly different climate regimes to those in the Levant and parts of Anatolia (Zittis et al., 2022). Additionally, there is great dependence on the $\delta^{18}O_{ca}$ proxy which itself is influenced by a variety of environmental and climatic factors, and so limiting its use as a pure rainfall amount signal (Cheng et al., 2015; Reuter et al., 2018; Fleitmann et al., 2025). Therefore, to help resolve the relationship between palaeoclimate and the rise of early complex societies in Mesopotamia, there is a clear need for multi-proxy palaeoclimate records sourced directly from the Mesopotamian region, and in close proximity to key ancient urban settlements (Fig. 1).

Development of palaeoclimate records in Mesopotamia has been substantially hindered by decades of political conflict, and the resulting difficulties for access to the most dependable terrestrial sites. In recent years, several caves in the karstic mountains of Iraqi Kurdistan have now become accessible to researchers, with several publications already highlighting their potential for use in palaeoclimate research (Flohr et al., 2017; Marsh et al., 2018; Al-Manmi et al., 2019; Sinha et al., 2019), and ability to provide important context for studying the drivers (and limiters) of complex societal development during the early-mid Holocene. One limitation, however, is that these records have been generally short-lived or offered limited clues about some of the earliest periods during the early-mid Holocene when settled life and eventually cities developed.

The recent publication of the Shalaii Cave palaeoclimate record (stalagmite SHC-03; Iraq) now offers an opportunity to explore socio-climatic interactions in Mesopotamia since ~ 10,560 BP (Fleitmann et al., 2025). Given that this earlier publication did not focus on the archaeological record in relation to the palaeoclimate record, our work attempts to address this by making that comparison for a period when urbanism began. Following decades of archaeological research in Eastern Syria, Northern and Southern Iraq, Western Iran, Southern Türkiye, and more recently Iraqi Kurdistan, scholars are now in a better position to provide a new assessment on the role of palaeoclimate and the rise of urbanism. By combining the insights offered by archaeological investigations with the recent stalagmite SHC-03 record, including settlement surveys, built architecture, and portable material culture data, here we explore the extent to which climate variability contributed to the rise of complex societies and developments in palaeoclimate during the mid-Holocene (6500–5200 yrs BP) in Mesopotamia.

2. Evidence from palaeoclimate records

Studies to date have typically used multiple regional palaeoclimate records to explore socio-climatic interactions in Mesopotamia and the wider Near East (Palmisano et al., 2021; Lawrence et al., 2022; Marchetti et al., 2025). Caves such as Jeita or Soreq have also become key archives for use in Mesopotamian-focused palaeoclimate studies (Bar-Matthews et al., 1997; Cheng et al., 2015). However, one problem is that these cave sites are somewhat distant from key early urban settlements, and so may not fully capture certain local-scale, societally critical changes in climate. Furthermore, the cave records are based on oxygen isotope measurements, which are influenced by several factors and not only by the amount of rainfall (Cheng et al., 2015; Reuter et al., 2018). To overcome this issue of distance and ambiguous climate proxies, we focus predominantly on data obtained from Shalaii Cave, and recently presented by Fleitmann et al. (2025). The paleoclimate record generated from this cave is known to sufficiently resolve climate variability in decadal to millennial time periods, but is also located closest to key archaeological sites, including Tell Brak, those across Northern Iraq, Uruk, and others discussed below. Additionally, the Shalaii dataset is comprised of multiple proxies. Furthermore,

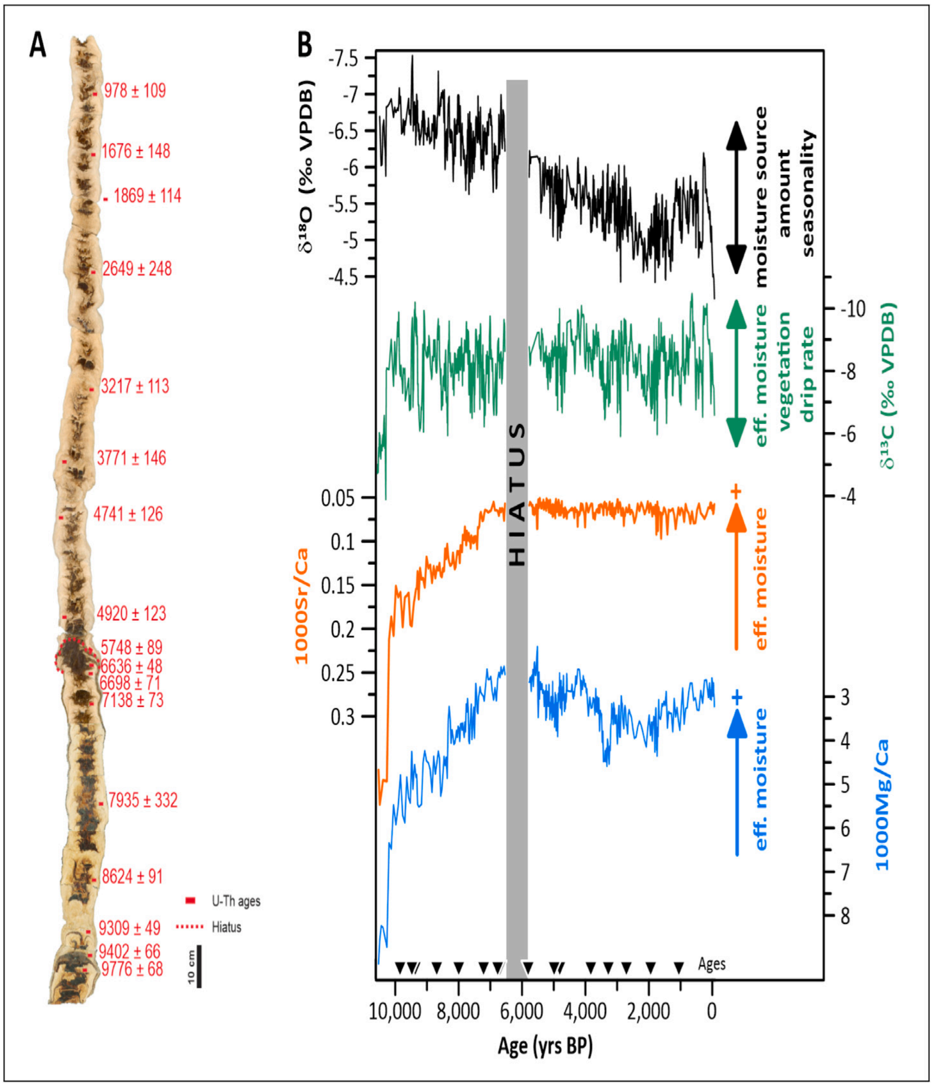

Fig. 2. The SHC-03 record (dates in years BP) and data from Shalaii Cave, including $\delta^{18}O_{ca}$, $\delta^{13}C$, Mg/Ca, and Sr/Ca (Fleitmann et al., 2025).

the variations in hydroclimate encoded in the Shalaii record show a strong relationship to atmospheric moisture for regions in Mesopotamia including Northern and Southern Iraq and Eastern Syria, meaning that the palaeoclimatic variations captured by this record are also likely to have affected our sites of archaeological interest.

Shalaii Cave (35.146°, 45.296°, 730 m.a.s.l) is located in modern Iraqi Kurdistan: in the northern region of Mesopotamia, but also in close proximity to several large Southern Mesopotamian sites (Fig. 1). This region today is characterised by large seasonal differences in precipitation, where rainfall is concentrated predominantly in the winter and spring months, and annual precipitation averages ~460 mm/year (Al-Manmi et al., 2019). Variations in Mg/Ca ratios within the SHC-03 record have been shown to provide a robust record of total effective moisture on long timescales, where longer residence times of groundwater within the karst aquifer during drier periods has been shown to increase the Mg content of cave drip water through incongruent dissolution of the partially dolomitised bedrock (Bajawan Formation) and so-called prior calcite precipitation (PCP) is greater during dry periods. Hence, higher Mg/Ca ratios in stalagmite SHC-03 are interpreted to signal lower effective moisture; as a direct response to reduced groundwater recharge, and longer bedrock-water interaction times (Fleitmann et al., 2025).

Although varied proxies have been collected, the Mg/Ca proxy shows greater efficacy for examination of local-scale changes in moisture compared to $\delta^{18}O_{ca}$, particularly with respect to the early-mid Holocene (Figs. 2 and 3). This also aligns well with Flohr et al. (2017). The $\delta^{18}O_{ca}$ record is less well suited to describe long-term (orbital) changes in the amount of precipitation, particularly during the early and middle Holocene when the moisture source effect is strongest due to the greatly enhanced Nile discharge and run-off along the coast of North Africa. Additionally, $\delta^{18}O_{ca}$ is influenced by several climatic factors rather than solely the amount of rainfall (so-called "amount effect"), whereas Mg/Ca is more directly influenced by changes in local water availability, making it a more sensitive indicator of hydrological variability. The climatic influences on $\delta^{18}O_{ca}$ are, therefore, non-stationary during the Holocene period of interest for this work relative to Mg/Ca. This is why we focus on using the Mg/Ca proxy here in evaluating the archaeological record within the context of the palaeoclimate results. Initially, in Shalaii Cave, Sr/Ca and Mg/Ca show a strong correlation (r >0.86) until 6540 yrs BP, but this correlation becomes diminished and is weak later (see Fleitmann et al. 2025 for further discussion). The SHC-03 Mg/Ca record suggests a continuous increase in effective moisture between ~10,500 and ~6700 yrs BP (just prior to the hiatus), and a period of maximum moisture reached between ~6700 and ~5200 yrs BP, with the absolute peak around ~5500 BP. The overall record spans nearly continuously from ~10,560 BP to the present and with a hiatus from ~6640-5750 yrs BP. The hiatus itself is unlikely climate-related, and is more probably the result

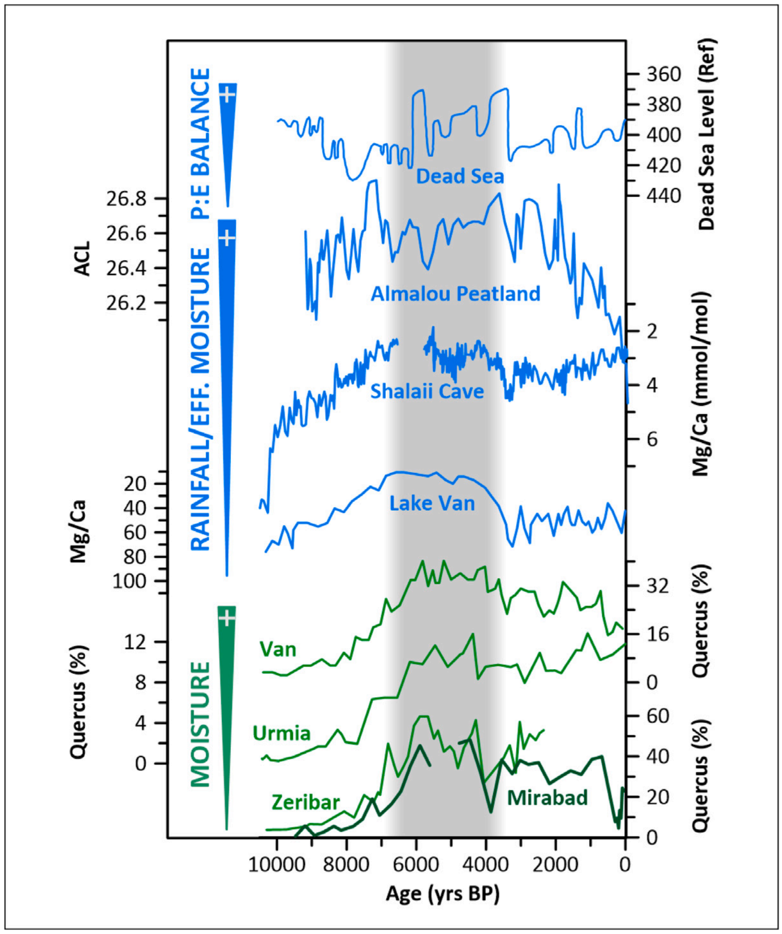

Fig. 3. Proxy data from the Holocene showing Shalaii Cave and nearby lake (Mg/Ca, precipitation–evaporation (P:E)), peatland (Average Chain Length (ACL)), and regional pollen data. The period 6500–3500 yrs BP is highlighted. Data derive from Dead Sea lake levels (Migowski et al., 2006), Almalou Peatland ACL (Chen et al., 2024), Mg/Ca records from Shalaii Cave (Fleitmann et al., 2025), and Lake Van (Wick et al., 2003). Quercus pollen records are from Van (Wick et al., 2003), Urmia (Stevens et al., 2012), Zeribar (Stevens et al., 2001), and Mirabad (Stevens et al., 2006).

of an earthquake — which prompted the slight change in the growth direction visible in the stalagmite.

Taken together, the Shalaii Cave palaeoclimate record produced by Fleitmann et al. (2025) shows that inland Mesopotamia experienced a relatively dry early Holocene, although still likely wetter compared to the Pleistocene, before the onset of an increasing moisture trend that reached a peak by the mid-Holocene (between approximately 7000 to 4000 yrs BP). Interpretation of the SHC-03 geochemical record suggests that regional hydroclimatic variability is driven by local processes, yet also influenced by a diverse range of systems and sources. For example, the Indian monsoon, the Mediterranean, and land–sea interactions over the Persian Gulf. During the early Holocene, a strong and extended monsoon season would reduce the total amount of precipitation in Mesopotamia by shortening the duration of the spring rainfall season, thereby reducing total annual precipitation (Stevens et al., 2006; Djamali et al., 2010; Fleitmann et al., 2025). The timing of the development of the Arabian anticyclone has been shown to play an important factor in spring rainfall (Mohammadi et al., 2021). More recent evidence for a more southerly location of the subtropical high during the mid-Holocene demonstrates shortening of the dry summer season, whereby the strength of the spring Arabian anticyclone is lowered and this results in higher spring precipitation (Chen et al., 2024). Furthermore, the Persian Gulf's slow inundation during the early-middle Holocene and shoreline approaching modern conditions has been shown to be an important moisture source during the spring months, potentially helping to provide sufficient rains for rainfed agriculture in northern Mesopotamia (Evans and Smith, 2006). Thus, existing evidence pertains to the emergence of a winter/spring-dominated rainfall regime during the mid- to late-Holocene (Wick et al., 2003; Fleitmann et al., 2025), with the Persian Gulf, Arabian anticyclone, and Indian summer monsoons greatly contributing to evident moisture increase seen in mid-Holocene Mesopotamia.

Proxy data from Shalaii Cave show good agreement with records across Southwest Asia (Fleitmann et al. 2025; Fig. 3). For example, there is support for a hydroclimate optimum between ~7500–3000 yrs BP in lipid biomarker records from the Almalou Peatland located in the western Iranian Plateau (Chen et al., 2024). The nearby Lake Van has Mg/Ca time-series data supporting lower salinity and greater rainfall between ~6200 and 4000 yrs BP, suggesting higher water levels, and pollen and Sr/Ca values from Lake Mirabad suggest generally lower lake levels prior to ~6000 yrs BP (Stevens et al., 2006). Similar agreement is also visible from comparison to palynological records from Lake Van (Wick et al., 2003), Zeribar (Stevens et al., 2001), Urmia (Stevens et al., 2012; Kong et al., 2022; Sharifi et al., 2023), where an increase in the abundance of deciduous oak, juniper, and various mesic forest trees corresponds to broad-scale tree expansion in the mid-Holocene, with an increase in precipitation and shortening of the dry season helping to facilitate this (Djamali et al., 2010). Conversely, longer summer droughts and lower total rainfall before ~7000 yrs BP would have inhibited seed germination and tree expansion in both Mesopotamia and the surrounding mountain regions. The results from Shalaii, therefore, help reconcile seemingly contradictory data between pollen and hydroclimatic scenarios derived from $\delta^{18}O_{ca}$, with mid-Holocene tree expansion in the Zagros–Taurus appearing to now more closely align with increasing moisture evidenced from speleothem records.

Based on the interpretation of Fleitmann et al. (2025), the $\delta^{18}O_{ca}$ record of SHC-03 is strongly impacted by millennial-scale variations in the $\delta^{18}O$ of surface water in the Eastern Mediterranean, the main source of moisture and rainfall in the northern Mesopotamia cave site. However, given our focus is primarily on the effects of hydroclimatic changes on urbanism (rather than the underlying climate dynamics), we do not discuss this proxy in further detail here.

3. Archaeological data

3.1. Northern Mesopotamia settlement and archaeology

Several lines of evidence support the argument that settlement, urbanism, and resource consumption expanded during the evident increase in moisture phase demonstrated in Shalaii Cave between ~ 7500 and 5200 yrs BP. First is regional survey data from Northern Mesopotamian sites, such as from the Jazira (Wilkinson and Tucker, 1995) and Northern Syria (Wilkinson et al., 2004; Ur and Wilkinson, 2008; Ur, 2010a), which demonstrate a trend of generally more numerous settlements with a larger total occupied area (Lawrence et al. 2016, Palmisano et al. 2021; Fig. 4) during this time. In fact, settled area effectively doubles ~6200 yrs BP. Although the coarseness of the survey data may fail to capture more transient intervals of settlement collapse and/or abandonment, the clarity of evidence for long-term population expansion between 6500 and 5200 yrs BP from survey areas closest to Shalaii could suggest that conditions had become much more favourable for a larger population during this time.

Moving even closer to Shalaii Cave, more recent and incomplete survey work in the Erbil Plain (~80 km away), shows a comparable trend in an increasing number and area of sites between the early-mid Holocene; corresponding to the Neolithic through the Late Chalcolithic archaeological periods (Ur et al., 2021). In Iraqi Kurdistan's Shahrizor and Navkur Plains, increasing settlement trends are also evident from the late Neolithic (7500 yrs BP) through the Late Chalcolithic (5000 yrs BP). However, similar to the Erbil survey, these are incomplete results in that not all areas were intensively surveyed (Altaweel et al., 2012; Morandi Bonacossi and Iamoni, 2015). In the Upper Diyala/Sirwan region about 100 km south of modern Slemani (Suleymaniyah), Iraq, survey results may show a decline in settlement between 6000 and 5200 yrs BP; however, these results could be obscured by later occupation (Casana and Glatz, 2012). Increasing animal husbandry, suggested by residue analyses on ceramics, indicates frequent meat consumption and animal products that could be better supported by favourable environmental conditions, such as higher rainfall (Perruchini et al., 2023; Glatz et al., 2024).

Detailed and intensive survey of other key urban sites in Mesopotamia further support intensification of urban expansion during the interval of increased moisture captured in Shalaii Cave. Of particular note is the site of Tell Brak, which underwent rapid expansion such that new regions became occupied with an extent of ~135 ha at ~5800 yrs BP (Ur et al., 2007; Oates et al., 2007). This expansion aligns well with increasing effective moisture witnessed in stalagmite SHC-03, as documented by a decrease in Mg/Ca (Fleitmann et al., 2025). Tell Brak documents a major shift not only in the size of the overall settlement, but also in the types of buildings and administrative capacity, that is through the use of glyptic devices, from ~6200–5900 yrs BP. During this phase, a large monumental building, with 1.86 m thick walls and among the first potentially secular buildings, is built (Emberling and McDonald, 2003; Oates et al., 2007). Larger buildings and more complex administration suggest greater political organisation that may relate to an expanding population. The large monumental building marks clear evidence for grain storage and the use of flax on the site, which all point to potentially sufficient water resources and abundant grain supply (Hald and Charles, 2008). Large-scale consumption of food is also suggested by the presence of multiple large ovens with widths about 3 m; suggesting they were used for a large number of people following ~6000 yrs BP. The many clay sealings further indicate the volume of goods manufactured and processed at the site as having increased and became substantial (McMahon, 2009).

From an agricultural perspective in Eastern Syria, evidence for more abundant crop remains, and shifts in the geochemistry of key plant proxies (e.g., $\delta^{13}C$ and $\delta^{15}N$), collectively point to enhanced resource availability, use, and distribution. Together, they pertain to agricultural extensification practices on agricultural fields at sites such as Tell Brak and others nearby, which further suggests expanding farming activity during the Late Chalcolithic, including between 6000–5500 yrs BP (Styring et al., 2017). Furthermore, many rapidly made ceramic vessels and faunal remains suggest a wide consumption of meat and an increase in resource production and use (Oates and Oates, 1994; Emberling and McDonald, 2002; Oates et al., 2005). Evidence for construction of the so-called 'Eye Temple' between 6000–5500 yrs BP (Mallowan, 1947; Oates et al., 2007) provides an additional source of evidence for increasing urban complexity, given its association with the growth of religious/spiritual institutions in the city and greater building size, which are provisioned with increased resources such as alabaster stones, other stone decorative elements, and likely wood resources.

Important to note is that the expansion of urban features, administration, and resource consumption is not limited to Tell Brak in Northern Mesopotamia. For example, evidence for expanding temple administrative activity is recorded at the nearby site of Tell Hamoukar, where stone stamp amulets are used in greater quantity at about the same period between 6000 and 5500 yrs BP (Reichel, 2002). The Tell Hamoukar region also has occupation of the low-density area Khirbet al-Fakhar between 6400 and 5900 yrs BP, reaching a size of 300 ha (Al-Quntar et al., 2011). This is substantially larger than the main site of Hamoukar, which expands to about 15 ha (Ur, 2010a) between 5900 and 5400 yrs BP. Another site that shows evidence for intense expansion during this interval is Tell Hawa to the east, which reaches a relatively large size of about 30–50 ha (Wilkinson and Tucker, 1995). Alongside evidence for spatial expansion during this time, there is evidence of growing urban and societal complexity. At Tepe Gawra, east of modern Mosul, a large (possibly) administrative building called the "round house" emerged around 6000 yrs BP, demonstrating increasing resource use as well as evidence for increasing administrative capacity (Tobler, 1950). The smaller site of Hacinebi also shows evidence of greater architectural differentiation and increased storage, with a wide (3 m) wall enclosure built with large storerooms (10 m long) placed nearby that indicates increased grain or food surplus (Stein, 2001).

Taken all together, the majority of Mesopotamian sites did not reach sizes much greater than 10+ ha before ca. 6000 yrs BP. On the other hand, sites such as Tell Hawa, Hamoukar, Tell Brak, and likely others do surpass this limit after 6000 yrs BP. We also suggest that this expansion is not limited to solely spatial extent, but also includes expansion and increase in the number of goods and resources found on sites. For example, sites show evidence for increased use of administrative devices such as glyptics to track resources, and larger, better provisioned institutions such as temples. Such examples point to a greater and higher quantity of goods found on sites as effective moisture increased.

3.2. Southern Mesopotamia settlement and archaeology

Sites in Southern Mesopotamia are, unfortunately, affected by poor chronological control, and less robust estimates for archaeological site areas. Furthermore, Southern Mesopotamia has generally depended on canals for irrigation, as the broad alluvial landscape enables wide-scale irrigation that would have supported settlements. This could make them potentially resilient to drought. Canals are also seen as

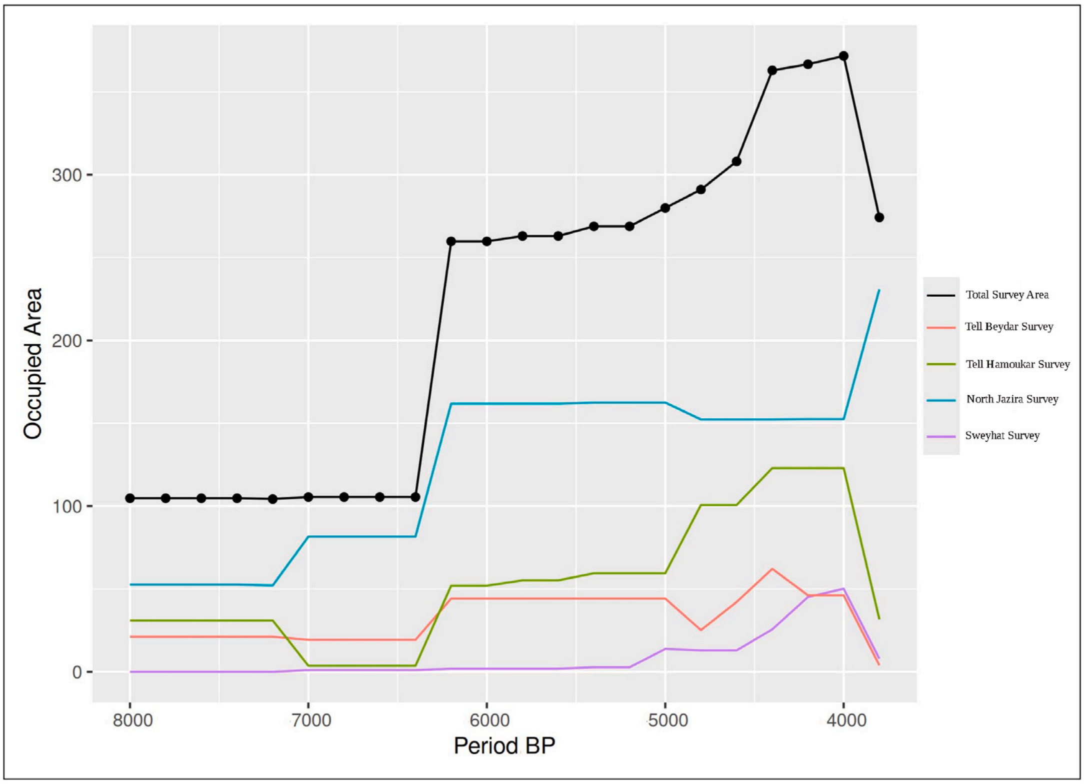

Fig. 4. Aggregate settlement survey data placed into 200-year bins from several relatively complete surveys among the nearest to Shalaii Cave in Northern Mesopotamia. The data show period (yrs BP) and occupied area (ha). Although dates for surveys are often coarse, the general trend indicates rapidly increasing settlement area between ~6500–5200 yrs BP (derived from Lawrence et al. 2016, Palmisano et al. 2021).

potentially beneficial for transportation, benefiting the growth of large urban centres (Algaze, 2008).

Evidence for increasing settlement complexity in Southern Mesopotamia between 6500 and 5500 yrs BP is discernible in the literature, and broadly comparable to trends observed in Northern Mesopotamia. For example, large-scale archaeological surveys in Southern Mesopotamia, including areas south of Baghdad, show settlement trends that pertain to an increasing number of settlements and site areas from the so-called Ubaid (7500–6000 yrs BP) to the Uruk periods (6000–5000 yrs BP) in the Diyala region to areas south near Eridu (Adams, 1965, 1972; Adams and Nissen, 1972; Gibson, 1972; Wright, 1981; Adams, 1981). Sites in the Diyala region just to the northeast of modern Baghdad also show signs of increasing social complexity, including greater evidence for centralised administration and organisation, and overall settlement area increase during the Ubaid phases. By 7000–6000 yrs BP at Tell Abada, administrative structures, protoliterate tablets, and increasing use of seals indicate greater administration. There is also a clear increase in ceramic production with the introduction of the potter's wheel that reflects likely greater resource consumption due to the presence of more rapid pottery manufacturing (Jasim, 2021). Excavations at sites such as Eridu also reveal increasing social complexity and more effective temple construction between 7000 and 5700 yrs BP, suggesting greater resource utilisation over the span of that time (Safar et al., 1981).

The development of protoliterate texts and writing by 5500–5300 yrs BP pertains to the use of new administrative tools. This likely occurred to facilitate the handling and management of an increasing number (and volume) of resources, such as food and textiles, from nearby regions (Glassner, 2003). The site of Uruk, which gives the name to the Uruk Period (ca. 6000–5000 yrs BP) in Southern Mesopotamia, exemplifies expanding urban life during the Late Chalcolithic, reaching an occupation of around 250 ha by 5200 yrs BP (Finkbeiner, 1991). However, it is not just the overall occupied area, but the clearly increasing use of resources through 5200 yrs BP becomes evident. Evidence for the earliest writing practices, focused on accounting for many goods, expansion of the city's main temple complexes and resources required for them, and construction of many new and large buildings built over an area of several hectares are all found in the city and between 6000 and 5000 yrs BP (Jordan, 1928; Liverani, 2006; Crüsemann et al., 2019)). The rapid growth and large scale of urbanism are not only unprecedented relative to previous periods, but they also reflect the first time where enormous quantities of resources and diversity of materials could be brought to Uruk. In particular, many items found at the site reflect long-distance trade contact with Anatolia, Iran, Central Asia, and other regions. Other sites such as Girsu and Nippur likely demonstrate large expansion in occupied area between 6000 and 5200 yrs BP. The site of Tell Uqair, about 80 km south of modern Baghdad, displays clear evidence of a large temple building that utilises more resource not only in construction but also in decorative elements such as paint used in the building as the town increased in occupied area (Lloyd and Safar, 1943). The full extent of some of these sites are not completely clear due to later building obscuring these sites, but recovered remains suggest activity greatly accelerated along with greater resource availability: both of which could have been made possible by favourable climatic conditions. Additionally, canal and irrigation channels from the mid-Holocene and between 5000–4000 yrs BP around Uruk show increasing stability and construction activity, suggesting an environment favourable for settlement and greater irrigation (Jotheri et al., 2018).

3.3. Expansion of Southern Mesopotamian culture and decline

Existing evidence points to clear expansion of key settlements in Northern Mesopotamia between 6200 and 5500 yrs BP. From ~5500 to 5200 yrs BP, this evidence shifts to demonstrate the increasing influence of Southern Mesopotamian culture into the northern regions, a phenomenon often called the “Uruk expansion” (Algaze, 1989). This includes influence such as increasing Southern Mesopotamian ceramics, and outposts on key sites in Northern Mesopotamia and large Southern Mesopotamian colonies, such as at Habuba Kabira and Jebel Aruda in Syria (Algaze, 2008). Plants found at Tell Brak suggest favourable growing conditions in the later part of the Late Chalcolithic, with potentially greater moisture favourable for later-flowering taxa and crops (Hald, 2008).

The expansion of Uruk culture in the north vanishes by around ~5200–5000 yrs BP and sites (e.g., Habuba Kabira, Jebal Aruda, Tell Brak) become abandoned or are reduced in scale (Frangipane, 2009). As a result, the ceramic material culture of Northern Mesopotamia, which included styles from both Northern and Southern Mesopotamia, reverts back to mainly local styles and suggests a reduction in interregional interaction and colonisation by Southern Mesopotamia. At the same time, larger settlements in Northern Mesopotamia are replaced by small and mound-based villages, where the disappearance of tokens, sealed bullae, and proto-literate cuneiform and/or administrative technologies are all indicative of a deurbanisation process. Although some large sites may maintain some urban characteristics (e.g., Tell Brak), the largest settlements become significantly reduced, and evidence for both economic specialisation and political power both reduce relative to earlier intervals. This period of ‘deurbanism’ in Northern Mesopotamia is in contrast to the situation in the south, where urbanism (also termed ‘hyper-urbanism’) is still observed (Adams, 1981; Akkermans and Schwartz, 2003; Ur, 2010a). This decline or deurbanism coincides with the Shalaii Cave record indicating increased aridity after ~5200 yrs BP, where the Mg/Ca proxy reverses from the earlier trend (Fleitmann et al., 2025). Although certainly other factors could be affecting settlement, constraints on moisture could complicate settlement expansion witnessed in the earlier wetter period.

4. Discussion and conclusion

The Shalaii Cave paleoclimate record provides evidence for a close coupling between hydroclimate and urbanisation processes in Mesopotamia between 6500 to 5200 yrs BP. Exploration of the relationship between palaeoclimate and the development of Mesopotamian urbanism during the mid-Holocene has been previously marred by uncertainties; largely due to poor chronological control, and a general lack of palaeoclimate records located in close proximity to critical urban centres. The Shalaii Cave record provides a unique, high-resolution, millennia-scale perspective on the palaeoclimate history of Northern Mesopotamia, and prompts important reconsideration of current theories to explain the urbanisation process in Northern Mesopotamia. By integrating this new record with existing archaeological evidence, our work shows that the earliest urban centres emerged during the highest levels of effective moisture in the entire Holocene for this region between 6500 to 5200 yrs BP, peaking at ~5500 yrs BP (Akkermans and Schwartz, 2003; Wilkinson et al., 2014; Lawrence and Wilkinson, 2015; Palmisano et al., 2021; Fleitmann et al., 2025). The temporal correspondence between these climate patterns (marked by increasing moisture), and expanding urbanism, support a correlation that would remain undetected if relying on solely distal palaeoclimate proxies. Furthermore, we suggest that the prior dependence on $\delta^{18}O_{ca}$ as a proxy for regional hydroclimate may have distorted the significance of the amount effect for Mesopotamia, causing fundamental issues for synthesis of key change-points in palaeoclimatic and archaeological data. Thus, Shalaii Cave is now able to provide a clearer picture that aligns well with other proxy records from across the region (e.g., lacustrine and pollen records), and so reconciles previously contradictory results.

Further support for a link between hydroclimate variability and societal evolution is identified at 5200–5000 yrs BP, where some larger sites are reduced or abandoned (e.g, Habuba Kabira), in conjunction with a decline in effective moisture (Fig. 3). Of course, it is likely that other (non-climatic) processes did play a key role in developing urbanism. We want to emphasise that not only climate is complex in relation to the role in played to the rise and evolution of urbanism, but key data are still required to better understand the relationship between the rise of early urbanism and climate. In particular, seasonal moisture fluctuations and variability affecting urban and non-urban, including nomadic, lifestyles may have been an important factor affecting a variety of societies.

Combining key archaeological evidence with the Shalaii Cave palaeoclimate record shows that the deurbanisation and “ruralisation” period in Northern Mesopotamia coincides with a distinct reduction in effective moisture, potentially the 5.2 K event or a rapid climate change (RCC) event (Mayewski et al., 2004; Clarke et al., 2016; Fleitmann et al., 2025). One possibility is this may have triggered migration to Southern Mesopotamia where agriculture is generally based on irrigation, and thus more resilient to drought. Settlement decline in Southern Mesopotamia is not as evident, but rain-fed Northern Mesopotamia would likely be more sensitive to a reduction in effective moisture. Settlements in Northern Mesopotamia do eventually recover after ~4700 yrs BP, which coincides with a second wave of urbanism in this region, where sites such as Tell Leilan, Tell Beydar, and Tell Brak flourish. The nature of urbanisation in this second phase is geographically widespread, and archaeologically almost simultaneous. Tell Leilan, Tell Mozan, and Hamoukar all grow from around 15 ha to 90–120 ha within a century and Tell Brak expands to 65–70 ha (Akkermans and Schwartz, 2003; Ur, 2010b; Wilkinson et al., 2014; Lawrence and Wilkinson, 2015; Lawrence et al., 2016; Palmisano et al., 2021).

Undoubtedly the relationship between climate and the rise and decline of urbanism are complex. We are not arguing for simple cause and effect processes between rainfall and urbanism. Rather, likely a variety of social and environmental factors affected the rise and decline of urban societies (Algaze, 2008; Lawrence et al., 2022). What we demonstrate here is that favourable moisture conditions not only coincide with the rise of urban-based societies but that conditions could now be demonstrated to show that they could provide an abundance of resources that facilitate urban expansion. On the other hand, data now clarify that declining rainfall could make urban expansion more difficult due to diminished resources. With the Shalaii Cave records and incorporation of archaeological data, this picture is more evident than previous arguments using more distant palaeoclimate archives and proxies that are less dependable than that evident in Shalaii Cave. We can see that the situation in Southern Mesopotamia could have been more complex than the Northern Mesopotamia as urban-based societies seem to have continued in Southern Mesopotamia during a decline in moisture around 5200 BP (Altaweel, 2019). The results support and show that Northern Mesopotamian settlements are more likely to be sensitive to increased and decreased moisture than Southern Mesopotamia; however, even here the coupling between rainfall and urbanism may not be direct given a variety of social and ecological factors.

Taken together, our work underscores the importance and value of further research in this domain. Seasonality is not well captured by current data; how settlement and different lifestyles in the mid-Holocene adapted or took advantage of seasonal change may need closer investigation. For example, given the more ephemeral nature of nomadic remains relative to settlements, the archaeological record does not well represent the role of nomadic societies during this time of palaeoclimate change. Nomadic lifestyles likely play an important and significant role, enabling settlements and societies to potentially adapt to uncertain climate during the mid-Holocene, but that relationship to settlement and evolving climate needs further work (Sundsdal, 2011; Potts, 2014). Given the migratory nature of these populations, closer exploration of their distribution, characteristics, and practices during the mid-Holocene could provide unique insights into the importance of seasonality, and the extent to which seasonal variations in climate shaped different social structures.

CRediT authorship contribution statement

Mark Altaweel: Developed, Planned, Writing – original draft. **Diary Ali Mohammed Amin Al-Manmi:** Conducted field research, Writing – original draft. **Andrea Squitieri:** Conducted background research on archaeological data, Writing – original draft. **Alice R. Paine:** Conducted background research around palaeoclimate, Writing – original draft. **Karen Radner:** Conducted field research, Writing – original draft. **Dominik Fleitmann:** Consulted on palaeoclimate data, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.quascirev.2025.109614.

Data availability

All data and/or code is contained within the submission.

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