# Human Settlement and Water Availability at the Qa' Shubayqa during the Terminal Pleistocene and Early Holocene

## Comparing Hydrological Models and Archaeological Data


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# Abstract


There is increasing evidence that wetland ecosystems played a key role in the transition from hunting and gathering to agriculture in southwest Asia. Yet, while they are ecologically rich, wetlands are also fragile and vulnerable to climate change and disruption by humans. Reconstructing the relationship between wetlands, human settlement and climate is therefore crucial to gain a better understanding of the emerging agro-ecological system during the Epipalaeolithic-Neolithic transition and how resilience articulated itself during this transition. Archaeological fieldwork in the Qa' Shubayqa in northeast Jordan has demonstrated that this area supported a marshland during the terminal Pleistocene and Early Holocene, which made this area attractive to Late Epipalaeolithic and Early Neolithic communities between 15,000 and 10,500 years ago. This period was marked by significant changes in human settlement patterns, economy, social organization and environment that culminated in the emergence of the first agricultural societies. To better understand how human groups reacted to and coped with changes in water availability, we compare hindcasted palaeoclimate hydrological models with archaeological data on water availability and settlement. These indicate that a substantial wetland environment could have existed at Shubayqa throughout the modelled period from 17,000 to 8000 BP and that it did exist during all attested periods of human settlement. Predicted drops in water availability are associated with periods of apparent settlement hiatus, but it remains

unclear whether this means that the wetland was reduced or disappeared. Though as ever contingent on new excavations providing additional evidence, our current reconstruction of water availability and settlement at the Qa' Shubayqa illustrates a clear but non-linear human response to climate change: prehistoric communities were able to thrive in this fragile environment during wet periods, but were not able to cope with dramatic drying, and not always quick to re-establish settlement after more favourable conditions returned.

# 1 Introduction

The question of resilience to climatic and environmental change in the context of the transition from hunting and gathering to agriculture in southwest Asia is closely linked to issues of abundance and reliability of water sources. It has been widely recognised that climatic change and resultant environmental conditions created both the opportunities for human communities, as well as imposing limitations on where, when, and how farming could be practiced (Rosen 2007; Zeder 2011; Rosen and Rivera-Collazo 2012; Jones et al. 2019; Hassan 2021). And while in the long run farming contributed to the emergence of more resilient societies, it was also not risk-free as new dependencies and trade-offs emerged.

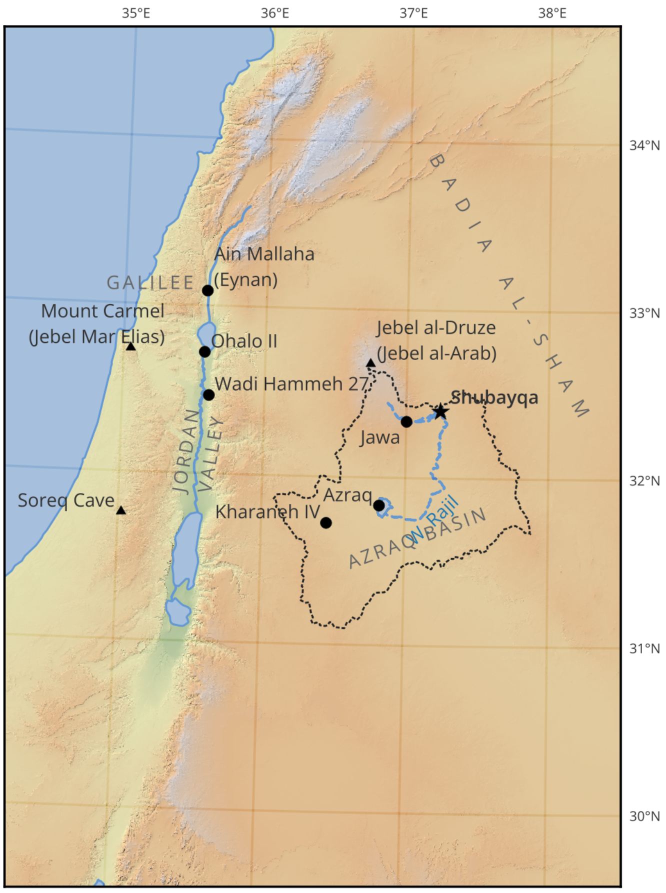


**Figure 1**: Location of Shubayqa and other sites discussed in the text within the Southern Levant.

Fieldwork in the northeastern *Badia* of Jordan, specifically around the Qa’ Shubayqa (fig. 1) has demonstrated that this region sustained long-term occupations by Late Pleistocene and Early Holocene groups. While substantial and long-lasting inhabitation of the Azraq region during the Epipalaeolithic and the PPNB had long been established (Maher et al. 2012; Garrard and Byrd 2013; Maher et al. 2016), the evidence from the Qa’ Shubayqa has demonstrated that hunter-gatherers were already present in the eastern *Badia* in the Early Natufian (Richter 2014a; Richter et al. 2016; Richter et al. 2017; Richter 2017a; Richter 2017b). This not only suggests a more or less continuous occupation of eastern Jordan during the Epipalaeolithic, but also that hunter-gatherer groups of the Late Natufian did not disperse into this area from a ‘core area’ centered on the Galilee, Mount Carmel, and the Jordan Valley, due to the effects of the Younger Dryas. Furthermore, the subsequent discovery of a substantial Pre-Pottery Neolithic A (PPNA) settlement at Shubayqa 6 not only demonstrated continuity of settlement into the early Holocene but also showed that this region forms part of the PPNA Levantine Corridor which was linked in to social, economic and cultural developments across the region.

Water availability was obviously a key factor in enabling human settlement. The Qa’ Shubayqa is nowadays situated at the 150 mm mean annual rainfall boundary and historically settlement across eastern Jordan was either transhuman and nomadic or, when more permanent, tied to reliable water sources, like the Azraq Oasis (Lancaster 1981). The discovery of dozens of Late Epipalaeolithic and PPNA sites dotted around the edge of the Qa’ Shubayqa raised the prospect that water was readily available to the Late Pleistocene and early Holocene inhabitants of the *qa’* (Arabic, plural *qa’en*, a mud flat/seasonal water body), perhaps from a marshland in the basin centre. As we will summarize below, zooarchaeological and archaeobotanical data provide ample evidence for the gathering of wetland and fully aquatic plants as well as the capture of wetland-dependent birds, clearly supporting the idea that the wetland was substantial enough to support these plant and animal communities. It is important to note that wetlands are being increasingly identified as ecotones that seem to have played a key role in the transition to plant cultivation in the Levant (Ramsey 2023). A better understanding of wetland ecosystems such as the Qa’ Shubayqa is therefore highly relevant to current debates on the impact of climate change in the transition to agriculture at the beginning of the Holocene. Yet the available data from the Qa’ Shubayqa derives from sources that are linked to human occupations and are therefore discontinuous, providing only a patchy picture. Geomorphological studies of the qa’ have to date not identified sediments dating to the Late Pleistocene or Early Holocene, which does not permit monitoring palaeoenvironmental conditions over a continuous time span independent of occupational periods (Jones et al. 2022).

The ambiguous and punctuated character of the available evidence therefore does not allow for a complete assessment of how climatic changes may have affected the availability of water in the *qa’*. Would water have been present in the qa’ year-round? How did climatic fluctuations affect water flow into the qa’ and evaporation of surface water? Archaeological data from excavations and surveys hint at possible breaks and disruptions in the occupation sequence, which raises the possibility that adverse climatic conditions could have disrupted settlement.

In this contribution, we tackle this issue of a disparate data set by using a computational approach in which we combine hydrological modelling and paleoclimatic hindcasting to predict the amount of water that would have flowed into the qa' and how much would have remained there under different climatic regimes. While modelling can obviously only provide us with different scenarios with variable reliability, we will compare the modeling results to the available archaeological, archaeobotanical and zooarchaeological evidence from the Shubayqa sites. This will then lead us to discuss issues of resiliency and their bearing on discussions concerning the transition from hunting and gathering to agriculture.

# 2 Drylands, Wetlands and Resilience

Resilience theory has thus far not featured especially prominently or explicitly in explanatory frameworks used to understand the transition from hunting and gathering to agriculture in southwest Asia (Rosen and Rivera-Collazo 2012; Ramsey et al. 2016; Hassan 2021; Ramsey 2023). In its archaeological incarnation, resilience theory conceptualises resilience as the capacity of a system to absorb disturbances and subsequently reorganize while retaining essential functions (Redman and Kinzig 2003; Redman 2005; Bradtmöller et al. 2017; Løvschal 2022). Archaeologists use resilience thinking to interpret periods of stability and transformation in past societies in an attempt to move beyond notions of linear progress or inevitable collapse models. Key ideas include the adaptive cycle – cycles of growth, conservation, release, and reorganization in societies – and cross-scale interactions (panarchy) where small-scale changes can cascade into larger crises or, conversely, where long-term memories enable communities to buffer against external challenges (Redman and Kinzig 2003). This perspective emphasizes that past human–environment systems often shifted between multiple stable states rather than a single equilibrium, with some traditions promoting stability and others enabling transformation. Resilience theory thus provides archaeologists with an approach that can help them conceptualize how ancient societies persisted, adapted, or redefined themselves in the face of environmental and social challenges. By examining long-term patterns, it can be highlighted how certain resource strategies or institutions enhanced durability, whereas inflexible practices sometimes led to vulnerability and collapse.

## *2.1 Water Availability and the Transition to Agriculture*

The transition from hunting and gathering to plant cultivation in southwest Asia occurred during a period characterised by unstable climatic conditions over the course of the end of the Pleistocene and Early Holocene. These cultural changes were however slow moving—on a scale of millennia rather than decades—and human–environment interactions in this period were highly dynamic. Short-term changes in rainfall patterns, vegetation and composition of faunal species could be easily compensated for by adjusting mobility patterns, foraging practices, and group size. Nevertheless, water is obviously a critical resource in drylands and of immense importance to hunter-gatherers and even more so to potential gatherer-hunter-cultivators of wild crops. Settlements were therefore commonly situated near reliable water sources, such as rivers, springs, lakes or wetlands (Ramsey 2023). Still, if reliable water access was uncertain, flexible food procurement regimes would have been a likely compensation measure: diverse portfolios of resources were used to avoid over-reliance on any single water-dependent food (Lancelotti et al. 2016; Ramsey et al. 2016).

Wetland ecosystems have therefore emerged as a critical focal point in southwest Asian archaeology for understanding how terminal Pleistocene and Early Holocene groups balanced food procurement practices with water availability. Research across the region shows that Late Pleistocene and Early Holocene hunter-gatherers gravitated toward marshes, lakes, and river floodplains, which would have provided abundant water, as well as a wide range of edible plants and rich animal life in otherwise sometimes harsh environments (Ramsey et al. 2015; Ramsey 2023). For example, the site of Ohalo II on the Sea of Galilee (23,000 BP) yielded a unique botanical assemblage of dozens of wild plant species, highlighting how a lakeshore camp could support broad-spectrum foraging (Kislev et al. 1992; Kislev 2002; Weiss et al. 2004; Nadel et al. 2012). The Early to Middle Epipalaeolithic aggregation site Kharaneh IV was likewise situated adjacent to a shallow lake (Jones et al. 2016; Ramsey et al. 2018). Similarly, Late Epipalaeolithic settlements like Ain Mallaha/Eynan in the Hula Lake basin in northeastern Israel (Ashkenazi 2004; Ashkenazi 2013), Wadi Hammeh 27 in the Jordan Valley (Edwards 2001), and Azraq 18 in eastern Jordan (Garrard 1991) were located adjacent to wetlands, streams and oasis springs that provided a rich and stable resource base. Key findings from these contexts indicate that wetlands were not just passive backdrops but active “engines” of early subsistence change and may have fostered experimentation with plant management well before formal cultivation occurred (Ramsey 2023). Indeed, Ramsey (2023) recently proposed that Levantine wetlands served as natural “domestication laboratories,” where repeated human use and niche construction (e.g. deliberate burning or transplanting of wild plants) enhanced local productivity and created conditions conducive to the later emergence of agriculture, and similar possibilities for manipulation of wetland ecosystems have been proposed for the Qa’ Shubayqa (Yeomans et al. 2024). Wetland-adjacent sites show extensive evidence of wild plant processing—such as grinding of wetland tubers and grains (Pedersen 2015; Pedersen et al. 2016)—signalling that wetlands as well as grasslands supported the intensive exploitation of a wide range of wild plants, including potential progenitors for later domesticates (Arranz-Otaegui et al. 2016; Arranz-Otaegui et al. 2018b; Arranz-Otaegui and Roe 2023).

While it seems clear that wetlands were key localities for Epipalaeolithic and PPNA/B communities that afforded a measure of resource abundance and diversity, reconstructing how reliably water was available in these areas is more difficult. It is not always clear whether these localities provided reliable water supplies during periods of climatic stress. By definition, the archaeological data only provides short-term and culturally filtered snapshots from periods when these areas were actively occupied and used by humans. This poses the question on whether any gaps in occupation occurred due to climatic stress and resultant reduction in water availability or reliability, or whether they were due to other reasons – is what we are seeing in the archaeological record due to lack of data or environmental conditions? This can sometimes be addressed by geomorphological analysis of lake and wetland sediments, but this may not always be possible or may not always provide a complete picture either, as in the Qa' Shubayqa for example (see Jones et al. 2022 and below). Understanding the resilience of Late Epipalaeolithic and PPNA/B communities inhabiting wetlands therefore requires us to better understand the hydrological conditions that existed in these "domestication laboratories", since cultural-ecological inheritance is dependent on an undisrupted presence of people in the same ecological zone over the long-term, and reliable and abundant water would have been key to this. We must develop a better understanding of the hydrological conditions through time to better gauge the resilience of these communities in the face of climatic change. This is especially true for the Qa' Subayqa, given its hydrological-geographic setting in an arid environment highly dependent on seasonal water flow.

In this chapter, we therefore want to examine how permanent and stable the wetland ecosystem in the Qa' Shubayqa could have been during the Final Pleistocene and Early Holocene, and how it may have responded to broader climatic shifts. In particular, how would decreases or increases in mean annual rainfall have affected the approximate amount of water that would have arrived in the basin? What would the effects of temperature changes have been on surface evaporation rates? Both of these parameters would have influenced whether open water would have been present in the qa' during any given year. Would broader climatic changes have had a significant effect on the perseverance of the Qa' Shubayqa's wetland? We aim to answer these questions using hydrological modelling based on modern rainfall and wadi flow data to inform a combined model of the past paleoenvironment and hydrological system. We then compare that data to what we know from the archaeological, archaeobotanical and zooarchaeological evidence, and discuss all of this against the background of resiliency during the Final Pleistocene and Early Holocene.

## 2.2 *Prehistoric Settlement of the Qa' Shubayqa*

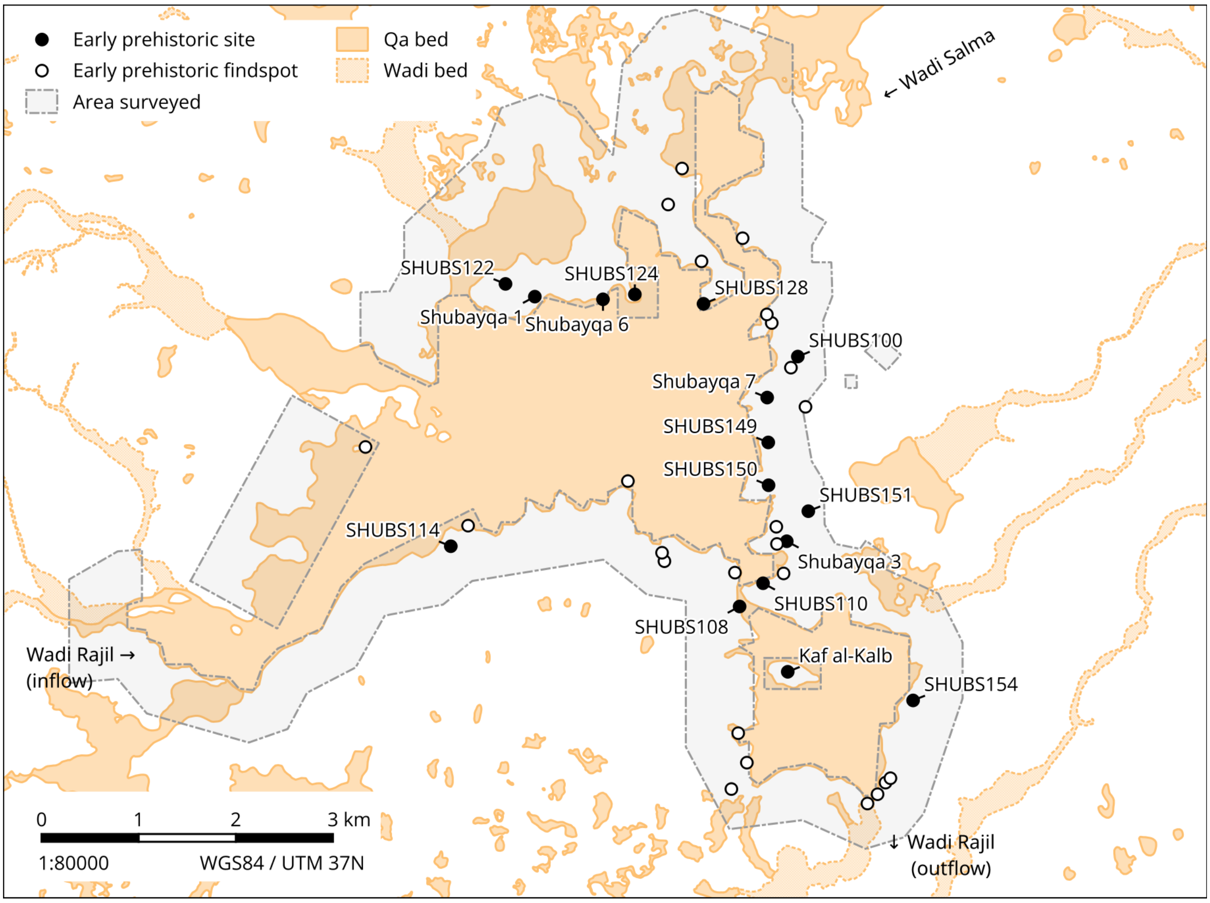


**Figure 2:** Early prehistoric archaeological sites around the Qa' Shubayqa

The Qa' Shubayqa (32.396° N, 37.239° E) is a seasonal water body that covers an area of c. 12 km$^2$. It is situated 25 km northeast of the modern town of Safawi in the eastern Badia of Jordan (fig. 1). The Wadi Rajil is the main source of water feeding the qa', draining from the higher rainfall area of the Jabal al-Arab/al-Druze and emptying out onto the Qa' Shubayqa from the west in a broad alluvial fan (fig. 2). This qa' is the first mudflat on the wadi's course towards Azraq. Several lesser tributary wadis flow into the Qa' Shubayqa from the north and east, including the Wadi Selma, which bring water from the high ground areas to the east of Shubayqa. Wadi Rajil drains out of the Qa' Shubayqa into an adjacent qa' to the southeast from where it continues to flow towards Jebel Qurma in the south, then turning west before it finally drains into the Qa' al-Azraq. The area surrounding the Qa' Shubayqa is characterised by gently sloping, low hilly country dominated by basalt boulders, outcrops and pavements that are the result of Miocene and Quaternary lava flows and subsequent erosion. The qa' itself is filled by fine-grained alluvial sediment. At present the qa' is almost level with only a gentle drop in elevation from west to east (c. 0.5 m km$^{-1}$) and north to south. In recent times, the qa' floods in late winter/early spring following the winter rains, though the amount varies considerably from year to year. Water remains in the qa' in small pools up until late spring and sometimes into the early summer, particularly in the lower lying south-east corner of the basin. This not only allows for significant vegetation to grow, but also attracts large numbers of birds to the area each spring. Bedouin nowadays use the qa’ to grow a variety of crops (Ben Mustapha et al. this volume), and herds of sheep and goat graze off the remaining vegetation after crops are harvested in late spring and early summer.

The qa’ contains up to 4.5 m of sediment with preliminary age estimates showing relatively younger sediments in the central part of the basin compared to those in the west, of early to mid-Holocene age, respectively, for the top c. 1.5 m of sediment (Jones et al., 2022). This pattern fits a basin filling with material predominantly from the Wadi Rajil, but the age of the lower sediments, and identification of any periods of non-deposition, are still to be determined. Archaeologically sterile sediments sitting beneath, and likely protected from deflation by, Shubayqa 1 have age estimates of c. 80 ka, which opens up interesting questions around the broader resilience of the Pleistocene landscapes of the region and how these changed with human activities through the Pleistocene–Holocene transition (Jones et al., 2022).

Archaeological fieldwork around the Qa’ Shubayqa combined with remote sensing since 2012 has documented intense settlement activity along the edge of the mudflat and its hinterland (fig. 2). ‘Desert kite’ hunting traps are especially concentrated to the north, east and south of the qa’, while numerous cairns, enclosures, field walls, wheelhouse-type structures, artefact scatters, and rock art and inscriptions are found on all sides of the qa’. An abandoned village site, Khirbet Shubayqa, is situated on the northern shore of the mudflat. Surface ceramic finds from this site suggest occupation during the Byzantine, Umayyad, and Ayyubid eras. Just over a thousand discrete archaeological sites have been identified to date in an area of c. 150 $km^2$. Of these, forty indicate the presence of a Late Epipalaeolithic and/or Pre-Pottery Neolithic occupation. Major excavations have thus far been carried out at two sites (Shubayqa 1 and 6), while sondages were excavated at six other localities (Shubayqa 3, SHUBS108, SHUBS110, SHUBS124, SHUBS149 and SHUBS150), and rescue excavations were conducted at one Late Neolithic cairn (SHUBS100; Richter 2014b; Richter 2017b; Richter 2017a).

In aggregate, the evidence suggests at times intensive occupancy of the Qa’ Shubayqa area both in prehistory as well as historic times. The number of Late Epipalaeolithic and Pre-Pottery Neolithic A sites dotted along the edge of the mudflat is particularly noteworthy, and suggests that the area was a preferred settlement spot during the transition from hunting and gathering to plant cultivation and animal herding. Radiocarbon dates have thus far been obtained from three sites (table 1): Shubayqa 1 (Richter et al. 2017), Shubayqa 3, and Shubayqa 6. The calibrated sequence of these ages show two major gaps: between c. 14,000 and 13,300 BP and c. 13,000 and 12,200 BP. While there is no obvious climatic explanation for the former gap, the latter corresponds with the conventional onset of the Younger Dryas and the drop in precipitation and temperature conventionally associated with it (Roberts et al. 2018; Jones et al. 2019). Although recent work has suggested that the impact of the Younger Dryas in the southern Levant may have been less environmentally severe than previously thought (Maher et al. 2011; Makarewicz 2012; Rosen and Rivera-Collazo 2012; Henry 2013; Caracuta et al. 2016; Hartman et al. 2016), it is nevertheless intriguing to note the correspondence between the gap in radiocarbon dates and the onset of the Younger Dryas. At the same time, we have to be mindful that this gap could also be an artifact of where excavations have thus far been carried out and from where samples were obtained and dated. Nevertheless, some of the zooarchaeological data discussed below also suggests the onset of drier conditions with the beginning of the Younger Dryas.

| *Lab identifier* | *Material* | *Taxon* | *Radiocarbon age (uncal BP)* | *Calibrated age (cal BP)* | *References* |
|---|---|---|---|---|---|
| **Shubayqa 1** | | | | | |
| Beta-112146 | dung | - | 12310±60 | 14820–14075 | [1] |
| RTD-7317 | tuber | *Bolboschoenus* sp. | 12289±46 | 14803–14073 | [1] |
| RTD-7318 | wood charcoal | *Zilla* sp. | 12332±46 | 14819–14104 | [1] |
| RTD-7948 | tuber | *Bolboschoenus* sp. | 12478±38 | 14979–14354 | [1] |
| RTD-7951 | tuber | *Bolboschoenus* sp. | 12166±55 | 14302–13814 | [1] |
| RTD-7311 | wood charcoal | *Vitex* sp. | 12367±65 | 14848–14135 | [1] |
| RTD-7312 | wood charcoal | *Zilla* sp. | 12405±50 | 14873–14221 | [1] |
| RTD-7313 | tuber | *Bolboschoenus* sp. | 12346±46 | 14826–14119 | [1] |
| RTD-7314 | tuber | *Bolboschoenus* sp. | 12273±48 | 14803–14059 | [1] |
| RTD-7315 | tuber | *Bolboschoenus* sp. | 12445±70 | 14979–14251 | [1] |
| RTD-7316 | wood charcoal | *Zilla* sp. | 12337±46 | 14821–14108 | [1] |
| RTD-7947 | tuber | *Bolboschoenus* sp. | 12322±38 | 14810–14104 | [1] |
| RTK-6818 | wood charcoal | *Fraxinus* sp. | 12477±76 | 15038–14279 | [1] |
| RTK-6820 | tuber | *Bolboschoenus* sp. | 12385±75 | 14906–14148 | [1] |
| RTK-6821 | seed | *Hordeum spontaneum* | 12385±78 | 14913–14144 | [1] |
| RTK-6822 | wood charcoal | *Tamarix* sp. | 12412±79 | 14949–14180 | [1] |
| RTK-6823 | wood charcoal | *Tamarix* sp. | 12321±78 | 14839–14069 | [1] |
| RTK-6813 | wood charcoal | *Tamarix* sp. | 12344±85 | 14851–14085 | [1] |
| RTK-6816 | wood charcoal | *Tamarix* sp. | 12389±78 | 14920–14151 | [1] |
| RTK-6819 | tuber | *Bolboschoenus* sp. | 11325±74 | 13326–13098 | [1] |
| RTK-6812 | wood charcoal | *Fraxinus* sp. | 11365±72 | 13403–13112 | [1] |
| RTK-6817 | wood charcoal | Chenopodiaceae | 11322±75 | 13326–13097 | [1] |
| RTD-8902 | wood charcoal | *Vitex* sp. | 10107±53 | 11923–11401 | [1] |
| RTD-8903 | wood charcoal | *Vitex* sp. | 10095±52 | 11872–11359 | [1] |
| RTD-8904 | wood charcoal | *Zilla* sp. | 10317±38 | 12459–11938 | [1] |
| RTK-6814 | wood charcoal | *Tamarix* sp. | 10229±70 | 12456–11644 | [1] |
| **Shubayqa 3** | | | | | |
| Poz-76086 | wood charcoal | *Fraxinus* sp. | 10170±50 | 11990–11415 | [4] |
| Poz-76088 | wood charcoal | *Tamarix* sp. | 10210±50 | 12095–11650 | [4] |
| Poz-76089 | wood charcoal | *Tamarix* sp. | 10090±50 | 11831–11355 | [4] |
| Poz-76090 | wood charcoal | *Tamarix* sp. | 10240±60 | 12448–11739 | [4] |
| **Shubayqa 6** | | | | | |
| Poz-76082 | wood charcoal | *Tamarix* sp. | 10050±50 | 11812–11336 | [4] |

| *Lab identifier* | *Material* | *Taxon* | *Radiocarbon age (uncal BP)* | *Calibrated age (cal BP)* | *References* |
|---|---|---|---|---|---|
| Poz-76082 | wood charcoal | *Tamarix* sp. | 10050±50 | 11812–11336 | [4] |
| Poz-76083 | wood charcoal | *Fraxinus* sp. | 9500±50 | 11073–10584 | [4] |
| Poz-76085 | wood charcoal | *Fraxinus* sp. | 9440±50 | 11062–10513 | [2,3] |
| RTD-9338 | wood charcoal | *Vitex* sp. | 9922±42 | 11604–11235 | [2,3] |
| RTD-9341 | wood charcoal | Salicaceae | 10035±43 | 11800–11324 | [2,3] |
| RTD-9342 | seed | *Hordeum spontaneum* | 9962±42 | 11682–11252 | [2,3] |
| RTD-9343 | wood charcoal | *Vitex* sp. | 10072±43 | 11813–11399 | [2,3] |
| RTD-9650 | wood charcoal | *Tamarix* sp. | 9892±28 | 11393–11234 | [4] |
| RTD-9653 | wood charcoal | *Zilla spinosa* | 9995±29 | 11686–11278 | [4] |
| RTD-9655 | tuber | *Bolboschoenus* sp. | 9431±27 | 10735–10578 | [4] |
| RTD-9656 | wood charcoal | *Zilla spinosa* | 10126±28 | 11874–11414 | [4] |
| RTD-9657 | wood charcoal | *Fraxinus* sp. | 10242±29 | 12040–11820 | [4] |
| RTD-9658 | tuber | *Bolboschoenus* sp. | 9425±27 | 10731–10576 | [4] |
| RTD-9659 | tuber | *Bolboschoenus* sp. | 9463±27 | 10993–10583 | [4] |
| RTD-9660 | wood charcoal | *Fraxinus* sp. | 9419±29 | 10733–10572 | [4] |
| RTD-9662 | wood charcoal | *Tamarix* sp. | 10087±28 | 11815–11404 | [4] |
| RTD-9663 | wood charcoal | *Fraxinus* sp. | 9549±28 | 11074–10715 | [4] |
| RTD-9664 | wood charcoal | *Vitex* sp. | 9598±27 | 11144–10771 | [4] |
| RTD-9665 | wood charcoal | *Tamarix* sp. | 9921±29 | 11399–11242 | [4] |
| RTD-9666 | wood charcoal | *Tamarix* sp. | 10240±29 | 12039–11819 | [4] |
| RTD-9667 | wood charcoal | *Tamarix* sp. | 10093±29 | 11819–11404 | [4] |
| RTK-7950 | wood charcoal | *Vitex agnus-castus* | 10270±33 | 12429–11824 | [4] |
| RTK-7952 | wood charcoal | *Vitex agnus-castus* | 10320±34 | 12455–11941 | [4] |

**Table 1**: Radiocarbon dates from Shubayqa used in this study, after [1] Richter et al. 2017, [2] Richter et al. 2016, [3] Yeomans, Martin, and Richter 2019, and [4] this study. Calibrated ages at 95% confidence were calculated using 'rcarbon' version 1.5.1 (Crema and Bevan 2020) with atmospheric data from Reimer et al. (2020).

# 3 Hydrological Modelling of the Qa' Shubayqa

The archaeological evidence is clear that a wetland was present at Shubayqa during periods of human settlement in the Late Pleistocene in Early Holocene (see below). However, the extent and persistence of this wetland remain difficult to establish. In addition, archaeo-environmental evidence can naturally only indicate whether water was present when people were, not whether it was absent during settlement hiatuses. Palaeoclimatic and hydrological modelling offers a complementary source of evidence that can answer these questions. We do not have sufficient palaeoclimate data or knowledge of the Shubayqa hydrological system to model water availability precisely or with certainty. However, we can put a number of quantitative constraints on the problem space that narrow the range of plausible hydrological scenarios.

The quantitative analyses described here were carried out in R version 4.5.1 (R Core Team 2025) and the add-on packages detailed below. The data and R code used to produce our results can be accessed via Zenodo at https://doi.org/10.5281/zenodo.17482936.

## *3.1 Basin Delineation*

To define the Shubayqa basin (fig. 2) we used a digital elevation model covering the eastern Jordanian Badia. This was extracted from NASADEM 1 arc-second, void-filled global topographic data (NASA JPL 2020) and reprojected to UTM zone 37 N. To prepare the elevation model for hydrological modelling, we applied the following preprocessing steps using WhiteboxTools (Lindsay 2016):

1. Smoothing (Sun et al. 2007; Stevenson et al. 2010).
2. Flattening of the area under the qa' to a constant elevation
3. Filling closed depressions to ensure flow across the entire study region

We traced the visible extent of the modern qa' bed from WorldView2 satellite imagery. Since the elevation model was preprocessed to flatten this area, we can consider the centroid of the qa' to be its outlet point for the purposes of the hydrological model. We then estimated the upslope watershed of this outlet point using the 'simple D8' flow direction algorithm (O'Callaghan and Mark 1984).

## *3.2 Palaeoclimate Simulation*

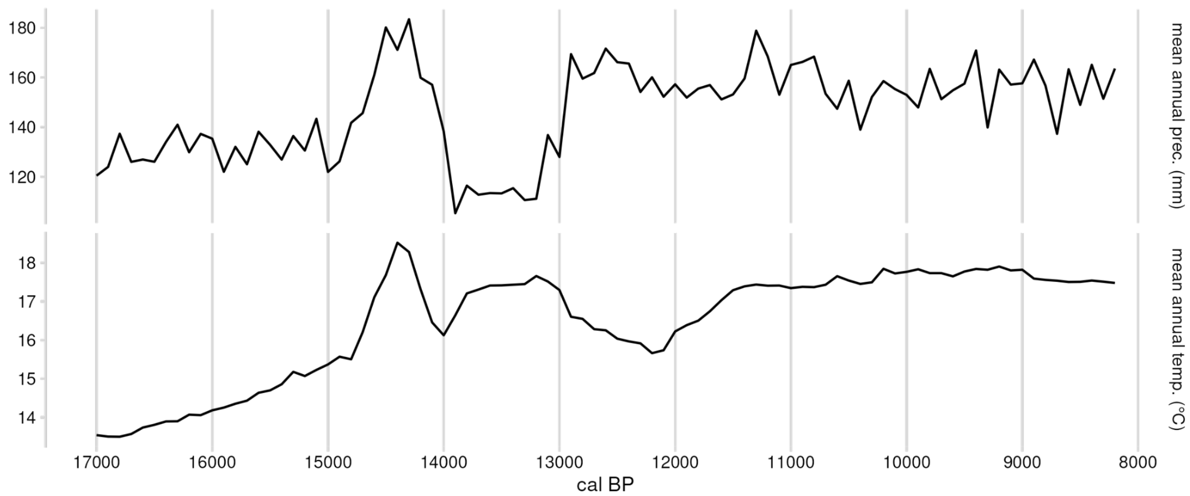


**Figure 3**: Simulated mean annual temperature at Shubayqa (32.40° N, 37.25° E) and mean annual precipitation over its catchment according to the CHELSA-TraCE21k experiment (Karger et al. 2023) from 17,000 to 8000 BP.

We used simulated palaeoclimatology from the CHELSA-TraCE21k experiment (Karger et al. 2023), extracting monthly precipitation over the Shubayqa basin and temperature of the qa' itself (32.40° N, 37.25° E) using the R package 'pastclim' (Leonardi et al. 2023). Our analysis is based on 89 time-slices from this experiment, covering the period from Heinrich Event 1 through to the end of the Early Holocene (17,000 to 8200 BP), at 100-year intervals. From this data we derived the mean annual temperature at the qa’ and mean annual precipitation across its catchment (fig. 3).

The climatologies produced by these experiments are models; although evaluated and calibrated against a wide range of physical archives (Braconnot et al. 2012), it is difficult to verify their predictions of past conditions (Raäisaänen 2007). In terms of hydrological modelling, their primary advantage is that they produce spatially and temporally continuous climate surfaces and directly predict climatic parameters with real units (i.e. mm precipitation and temperature in °C), in contrast to the system-specific annual proxies (Wilby et al. 2000; Wilby 2010). This makes them a complementary and relatively underutilised data source for archaeo-environmental studies which could be more widely used now the results of hindcasting experiments have been made openly available in high spatial and temporal resolution (e.g. Fordham et al. 2017; Brown et al. 2018; Karger et al. 2023).

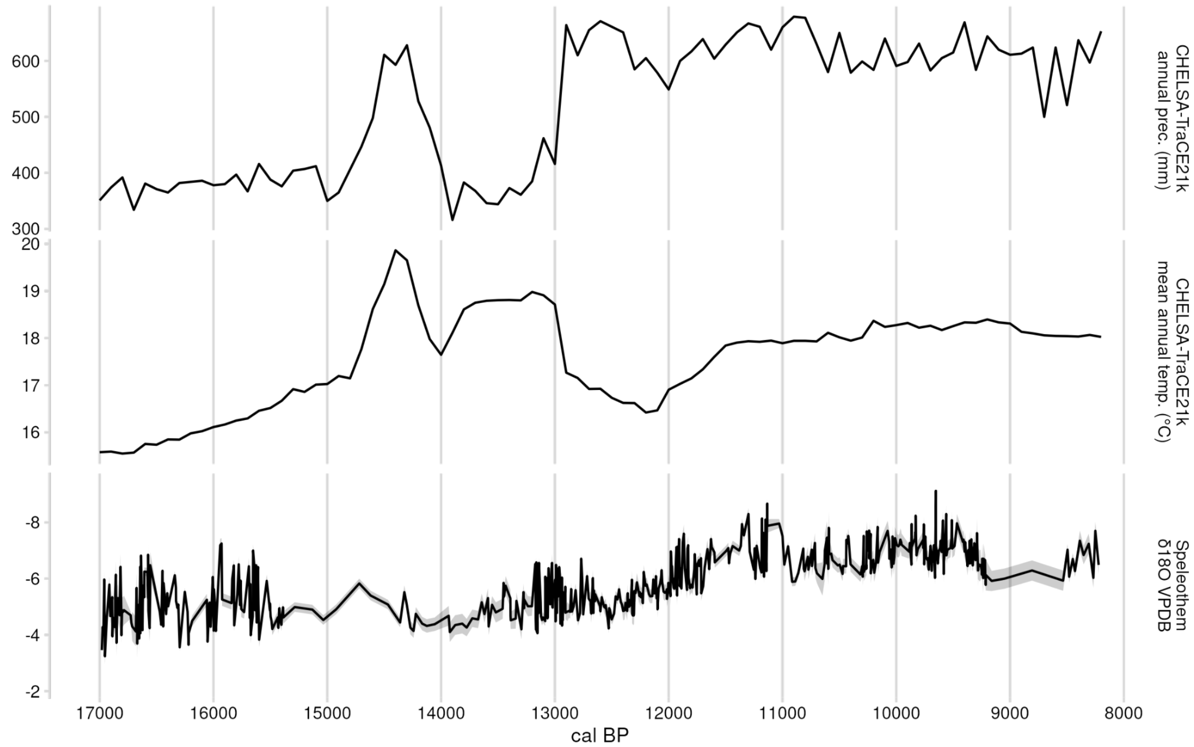


**Figure 4**: Simulated mean annual temperature and precipitation at Soreq cave (31.76° N, 35.02° E) according to the CHELSA-TraCE21k experiment (Karger et al. 2023) from 17,000 to 8000 BP.

To assess the congruence of this data for the southern Levant region, we compared the oxygen isotope record at Soreq cave (Bar-Matthews et al. 1997; Bar-Matthews et al. 1999; Orland et al. 2012) with the simulated climate at the same location according to the CHELSA-TraCE21k experiment. Simulated annual precipitation and mean temperature are broadly consistent with the Soreq speleothem isotope record (fig. 4), indicating a gradual transition from cold/dry conditions in the Pleistocene to warm/wet conditions in the early Holocene, and many of the centennial-scale fluctuations are aligned in both signals. Notably, however, the large fluctuations between 15,000 and 13,000 BP predicted by climate modelling are not present in the Soreq record. The sample density of the speleothem record is low over this period, but otherwise we have no ready explanation for this discrepancy.

## *3.3 Water Balance Model*

We calculated the volume of water potentially entering the qa’ annually as the sum of simulated precipitation over the area of its upstream basin (715,301,818 $m^2$).

Following similar work on Eski Acıgöl in Turkey (Jones et al. 2007), we estimated monthly potential evapotranspiration ($E$) from the qa’ surface using a simplified version of Penman’s formula (Linacre 2003:89) implemented in the R package ‘SPEI’ (Beguería and Vicente-Serrano 2023). Our estimation of evaporation is based primarily on the simulated monthly minimum and maximum temperatures from the CHELSA-TraCE21k experiment. Data on monthly average wind speed and daily solar radiation in the past was not available, so we replaced these with available modern measurements from Safawi (Ammari et al. 2015) and Ruwayshed (Jibril 1991), respectively. Solar radiation was estimated from latitude (32.4° N) and dew point/actual vapour pressure was estimated from the simulated mean minimum temperature.

Adapting the simple water balance model based on that used by Whitehead et al. (2008) for the nearby Jawa system, for the qa’ to have constituted a permanent (year-round) water body the volume of water entering it must have been greater than the volume that left it due to evaporation from the qa’ surface:

$$k\Sigma R > EA \cdot 10^{-3}$$

Where $\sum R_E$ is the simulated total effective rainfall across the upstream catchment ($m^3\ yr^{-1}$); $k$ is a constant representing the proportion of rainfall that remains in the qa after accounting for a variety of factors that we cannot presently empirically constrain (infiltration, losses to vegetation, overflow, etc.); $E$ is potential evaporation ($mm\ yr^{-1}$) from the qa’ surface; and $A$ is the surface area of the qa’ holding water ($m^2$). Assuming $R_E$ and $E$ are within an order of magnitude of each other, the balance of this equation is clearly primarily determined by $k$, which is difficult to empirically assess but which Whitehead and colleagues estimated at between 0.01 and 0.03 for Jawa, and the surface area of the qa $A$. As such, in calculating water balance for Shubayqa we make the simplifying assumption that $R$=$R_E$ – that is, that evapotranspiration *en route* to the qa’ is negligible compared to evaporation from its surface ($E$) and the poorly-constrained constant $k$.

## 3.4 *Modelled Hydrology*

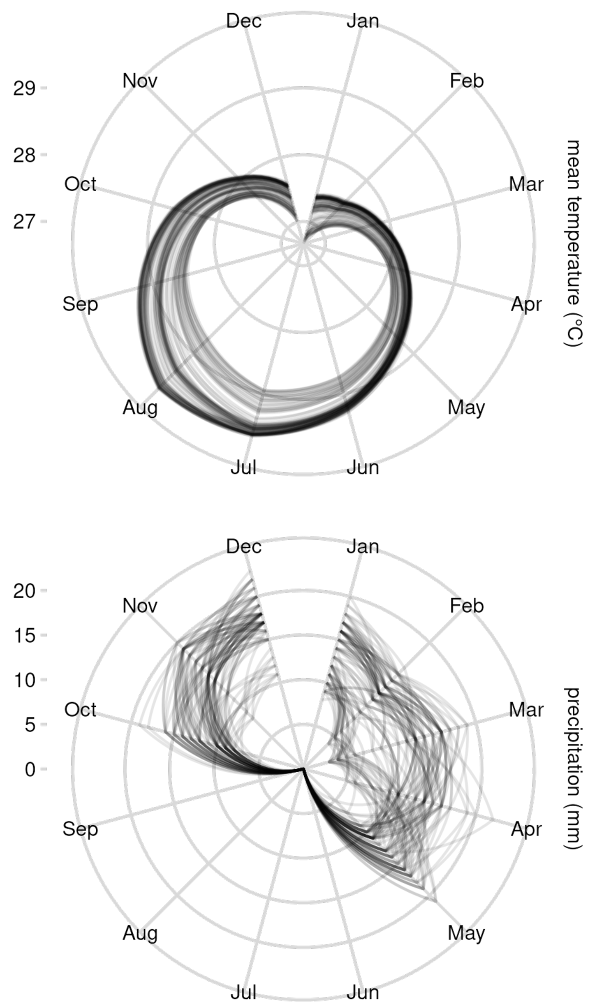


**Figure 5**: Simulated monthly mean temperature (top) and precipitation (bottom) at Shubayqa over the period 17,000–8000 cal BP, according to the CHELSA-TraCE21k experiment (Karger et al. 2023). Each line represents a simulated year at intervals of 100 years.

The CHELSA-TraCE21k simulation indicates that during the period from 17,000 to 8000 BP, Shubayqa (and the wider Southern Levant), experienced a similar rainfall pattern as today, with c. 100–200 mm of rain falling exclusively in the winter months (October–May, see fig. 5) on a declining west-to-east gradient. This suggests that it was subject to the same Eastern Mediterranean system that operates today and that fluctuations in precipitation were driven by changes in the steepness of rainfall gradient rather than a qualitative shift, consistent with previous findings (Enzel et al. 2008). Mean temperature changed more substantially, rising by 2–3 °C between the Pleistocene and Holocene (fig. 3), though as discussed in more detail below, a concurrent increase in precipitation appears to have mitigated any potential aridification.

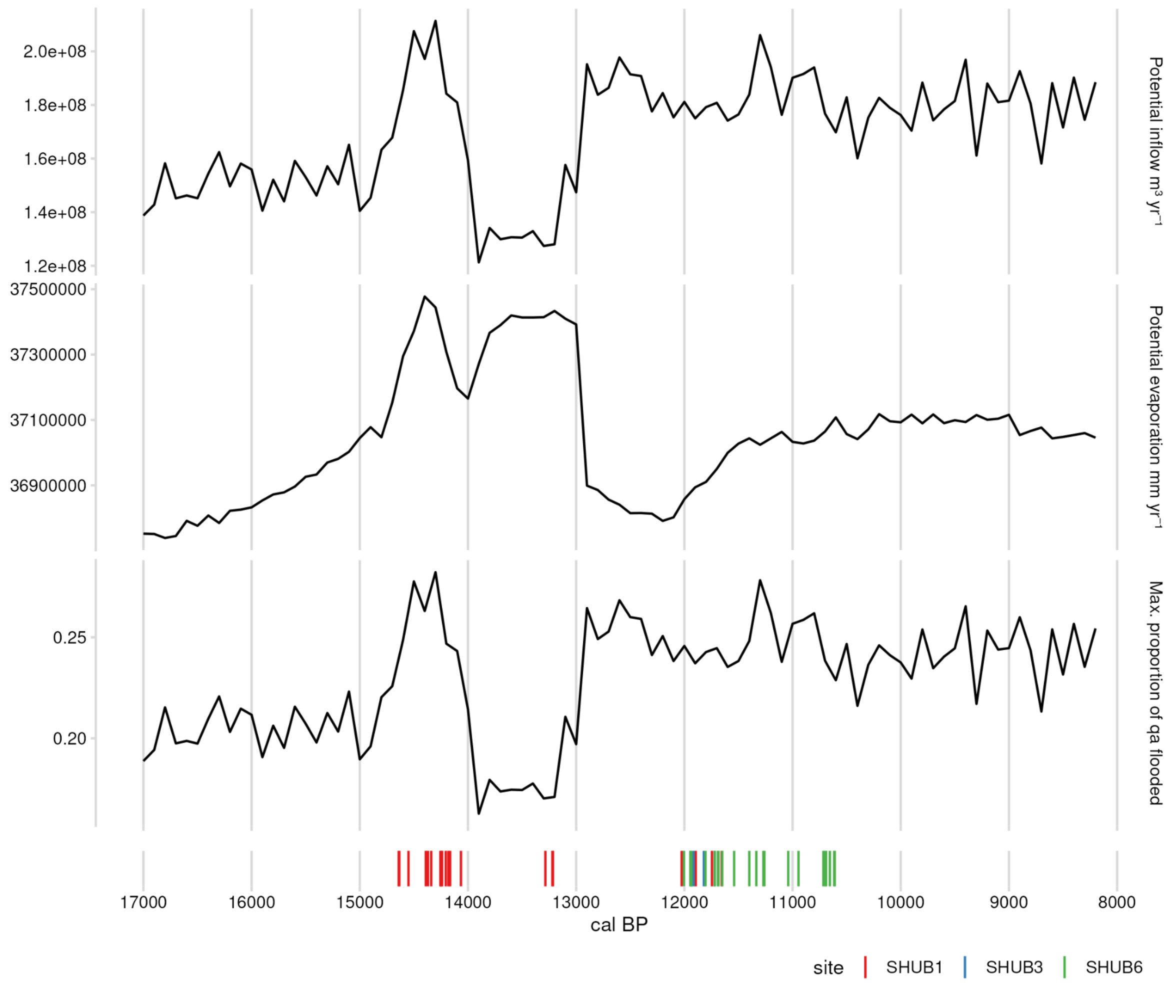


**Figure 6**: Modelled hydrology of the Qa' Shubayqa between 17,000 and 8000 BP compared to archaeological proxies of occupation and environment. From top to bottom: potential volume of rainfall from the upstream catchment; potential evaporation from the qa surface; maximum proportion of the current qa surface flooded that sustains a positive water balance assuming $k$=0.05; barcode plot of radiocarbon dates from Shubayqa 1, 3, and 6.

Annual potential evaporation from the qa surface is modelled to be an order of magnitude greater than potential inflow for the whole period 17,000 to 8000 BP (fig. 6), so it is unlikely that there was ever a permanent year-round water body with the same extent as the current mudflat. A positive water balance is however plausible for smaller portions of the qa basin and/or for parts of the year.

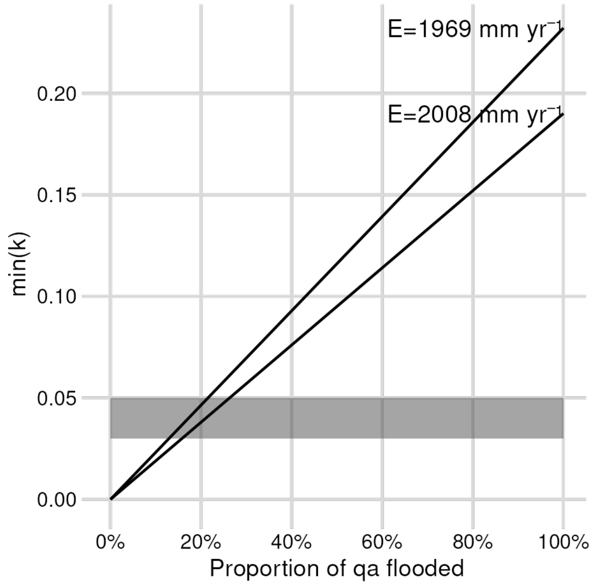


**Figure 7**: Minimum value of the constant *k* required for positive water balance depending on the proportion of the qa surface that is flooded, under high and low evaporation scenarios. Shaded area indicates the plausible range of *k* estimated by Whitehead et al. (2008).

Figure 7 shows the effect of varying the proportion of the current qa' bed that is assumed to have been flooded on the minimum value of the constant *k* (which represents losses to infiltration, evapotranspiration, outflow, etc.) required to obtain positive water balance from the equation above. Whitehead et al. (2008) estimated plausible values of *k* to be in the range 0.02 to 0.05; following this, around 10–30% of the qa's current area could have been flooded year-round, given the range of modelled potential evaporation values.

If we assume *k*=0.05 (the upper end of Whitehead and colleague's range), we can calculate the maximum permanently-flooded area given the volume of inflow and potential evaporation we have modelled from the palaeoclimate date (fig. 6). Without being able to quantify the depth of potential sub-basins or, consequently, their outflow point, we are unable to constrain the minimum (or likely) volume of these hypothetical water bodies. The effect of fluctuations in mean temperature on evaporation are insignificant, so the relative potential water level is essentially a function of incoming rainfall.

# 4 Archaeological Evidence of Wetland

Excavations at Natufian Shubayqa 1 (occupied c. 14,600–14,000 and 13,300–13,000 BP) and Natufian/PPN Shubayqa 6 (occupied from c. 12,400–10,500 BP) have yielded numerous lines of environmental archaeological evidence for the presence of water during periods of occupation at the sites. This evidence, summarised below, comes primarily in the form of dated remains of water-dependent bird, mammal and plant species.

## *4.1 Zooarchaeology*

Faunal remains from Shubayqa 1 and Shubayqa 6 provide strong support for the existence of wetlands in the Qa' Shubayqa throughout the Late Pleistocene and Early Holocene (Yeomans et al. 2017, 2018, 2024). They reveal a dynamic wetland ecosystem that endured through significant climatic fluctuations, as reflected in the composition and life-history signals of key bird and mammal species. During the Early and Late Natufian at Shubayqa 1 (ca. 14,600–14,000 and 13,300–13,000 BP, respectively) faunal assemblages at Shubayqa 1 are dominated by water-dependent birds, particularly ducks (Anatinae), geese (*Anser* sp.), swans (*Cygnus olor*), waders (Charadriiformes), rails (*Rallidae*), and grebes (*Podiceps* spp.) (Yeomans et al. 2017). The presence of both adult and juvenile bones, as well as eggshell fragments of Anatidae and swans (Codlin et al. 2025), is especially telling. Juvenile bones and eggshells indicate not just seasonal visitation by migratory birds during the winter months, but also local breeding, which requires persistent standing water from spring through late summer. Such breeding activity can only occur where water bodies remain throughout the reproductive cycle, which provides a direct proxy for reliable wetland conditions.

Shubayqa 1 was re-occupied after a settlement hiatus between 13,000 and 12,500 BP, which lasts for a significant proportion of the earlier part of the Younger Dryas. As Shubayqa 1 is re-occupied, Shubayqa 6's corresponding early occupation also begins at c. 12,400 BP. While some of the layers at Shubayqa 1 initially showed fewer avifaunal remains, newer evidence complicates the picture. The presence of eggshell fragments and juvenile waterfowl (including swans and geese) from Younger Dryas contexts at both Shubayqa 1 and Shubayqa 6 confirms that water bodies persisted, enabling successful breeding despite inferred regional climatic cooling (Yeomans et al. 2017; Yeomans 2018; Yeomans 2025). Notably, the abundance of mute swan remains during this period at Shubayqa 6 suggests that the area provided suitable, year-round water and vegetative cover necessary for these demanding breeders (Yeomans 2018; Yeomans 2025). In addition, the sustained presence of water-dependent mammals, such as wild cattle (*Bos primigenius*), underscores the continued viability of local wetlands during this interval (Yeomans et al. 2017; Yeomans 2018).

With the onset of the Early Holocene evidence for wetland conditions is further strengthened:  the PPNA faunal assemblage from Shubayqa 6 is again dominated by waterfowl, including ducks, geese, swans, and grebes. The continued presence of juvenile bones and eggshells underscores the ongoing suitability of the area for breeding populations, which in turn implies the presence of significant wetland environments close to the site (Yeomans 2018; Yeomans 2025). Shifts in the composition of the bird community, such as a relative decline in waders and increase in swans and grebes, likely reflect subtle changes in water depth or the extent of open water but do not indicate a loss of wetland persistence.

Taken together, the Shubayqa 1 and 6 faunal remains, particularly the simultaneous presence of both wintering and breeding waterfowl, as well as water-dependent large mammals, demonstrate that viable and predictable seasonal water bodies existed in the Qa'

Shubayqa during periods of occupation (Yeomans et al. 2017; Yeomans 2018; Yeomans 2025). This is even true for the later part of Younger Dryas, contradicting earlier interpretations of regional aridity, and highlights the importance of local hydrology in shaping long-term ecological stability. It is important to bear in mind, however, that no faunal data is available for periods of settlement hiatuses between c. 14,000 and 13,300 BP and 13,000 and 12,500 BP. Whether these gaps truly reflect gaps in the local settlement sequence or whether they are due to a shift in settlement patterns when other localities were occupied or due to sampling biases is at present not clear. Nevertheless, it can be safely stated that during the periods of occupation the Qa' Shubayqa wetlands supported abundant migratory and breeding bird populations of ducks, geese, swans and waders.

## *4.2 Archaeobotany*

The archaeobotanical remains from Shubayqa 1, 3 and Shubayqa 6 offer direct evidence to reconstruct local vegetation and provide key insights into past water availability. The wood charcoal and non-woody plant assemblages from the sites show that the vegetation during the late Pleistocene and early Holocene period comprised a wide range of plants including aquatic species (hydrophytes), wetland or riparian plant taxa (hygrophilous) and terrestrial species – primarily dryland steppe vegetation (Arranz-Otaegui et al. 2018b; Aldaia Aierbe et al. in prep.; Proserpio et al. in prep.).

Aquatic plants grow fully submerged, floating, or rooted in water. Their presence in the archaeological record from Shubayqa 1 and 6 is a strong indicator for the presence of permanent water resources during the terminal Pleistocene and the Early Holocene periods (Aldaia Aierbe et al. in prep.; Proserpio et al. in prep.). The seeds of pondweeds (*Potamogeton* sp.), water plantain (*Alisma* cf. *plantago-aquatica*) and flowering rush (*Butomus umbellatus*), in the studied assemblages provides direct evidence for the existence of significant areas of open waters, whereas the green algae oogoniums of *Chara* sp., also discovered among the charred plant remains, indicate the presence of a rich aquatic ecosystem.

Nevertheless, the majority of the plant taxa identified at these sites correspond to wetland species. Wetland plants occupy the ecological zone between aquatic and terrestrial environments, and a rich variety of both arboreal and herbaceous taxa have been documented in the wood charcoal and non-woody assemblages. Riparian trees comprise tamarisk (*Tamarix* sp.), ash (*Fraxinus* sp.), and poplar/willow (Salicaceae), species that need a stable supply of water to thrive. Chaste tree (*Vitex* sp.), which is the most abundant species in the wood charcoal assemblage of Shubayqa, is also a bush adapted to riparian settings and seasonal streams (Aldaia Aierbe et al. in prep.). Apart from these, various members of the Cyperaceae family were found in Shubayqa, such as club-rushes (*Bolboschoenus glaucus*/*Schoenoplectus* sp.) and spikerushes (*Eleocharis* sp.); hygrophilous plants growing in damp soils (Proserpio et al. in prep.). One of the most significant discoveries at Shubayqa 1 was the recovery of charred club-rush (*Bolboschoenus* sp.) tubers, which were found in large quantities within ancient fireplaces (Arranz-Otaegui et al. 2018a).

This plant thrives in shallow water or waterlogged soils, indicating that standing water was present for much of the year. The repeated presence of club-rush remains in multiple occupation layers suggests that the wetland was a persistent feature of the landscape, rather than a short-lived phenomenon when the sites were occupied. Other wetland taxa identified include common bulrush (*Schoenoplectus lacustris*) and common reed (*Phragmites australis*), both of which require high moisture levels to survive. The presence of a wide range of wetland species indicates that the qa' supported dense marsh vegetation, likely forming an extensive reed bed along its shores. Such conditions would have provided abundant resources, including edible seeds and tubers, raw materials for construction, and habitat for aquatic fauna.

However, some changes are observed in terms of the evolution of aquatic and wetland plant communities over time. The wood charcoal assemblage maintains a consistent taxonomic composition throughout the Natufian period. It is noteworthy that Salicaceae disappeared from the record in the late Younger Dryas (Aldaia Aierbe et al. in prep.). In the case of the carpological assemblage, the record shows a remarkable presence of aquatic species in the Early Natufian occupations in Shubayqa 1 (14,600–14,000 BP) and later, primarily during the PPNA phases of Shubayqa 6 (after 12,500 BP), which would be consistent with permanent sources of water (Proserpio et al. in prep.). However, these taxa are not well documented during the Late Natufian (13,300–13,000 BP at Shubayqa 1, 12,600–11,700 at Shubayqa 6), which suggests a deterioration in the conditions of the water bodies in Qa' Shubayqa that could be linked to the onset of the Younger Dryas. However, this evidence should be interpreted with caution, as the Late Natufian assemblages from Shubayqa 1 and 6 date to just before and during the final stages of the Younger Dryas. As a result, the dataset does not capture the full extent of ecological change during the climatic peak of this event, limiting our ability to assess how plant communities may have responded during its most critical phases. Nevertheless, the continued presence of Cyperaceae throughout the entire Natufian sequence (Early and Late Natufian) and also during the Khiamian-PPNA phases suggests that at least some marshland environments persisted despite broader environmental fluctuations of the Younger Dryas–Early Holocene transition.

Aside from aquatic and wetland communities, the wood charcoal and seed analysis also reveal the presence of grasslands and steppe vegetation close to the site. Firewood from steppe shrubs such as *Zilla spinosa*, Chenopodioideae, *Capparis* sp. and *Zygophyllum* sp. suggests that while the qa' was well-watered, its immediate surroundings consisted of drier scrubland. These drylands were mainly supported by herbaceous taxa like Poaceae, and various types of Brassicaceae and Fabaceae. This contrast highlights the oasis-like nature of Qa' Shubayqa, where a rich wetland existed within an otherwise arid environment. After the Younger Dryas a change is observed in this environment, with an increasing appearance of Irano-Turanian taxa like *Amygdalus* sp. and *Pistacia* sp. in the wood charcoal and carpological records, indicating the presence of scattered trees in this dryland steppe environments, perhaps due to changes in rainfall seasonality. Thus, the combined zooarchaeological and botanical evidence from the Qa' Shubayqa strongly supports the existence of a wetland ecosystem that persisted, albeit with fluctuations, throughout the

Late Pleistocene and Early Holocene. While there are gaps in the data due to apparent settlement hiatuses at Shubayqa 1, these cannot a priori be taken to imply that local conditions became too dry for wetlands to persist. To clarify this question, we now turn to modeling rainfall and evaporation rates and hindcasting them to the Late Pleistocene and Early Holocene.

# 5 Human Settlement and Water Availability

Palaeoclimate and water balance modelling indicates that there could have existed a substantial wetland environment at Shubayqa throughout the period 17,000–8000 BP, covering up to a third of the current area of the floodplain. Zooarchaeological and archaeobotanical evidence confirms that such an environment was present during all periods of known human occupation at the qa’ (c. 14,600–14,000 BP, 13,300–13,000 BP, and 12,000–10,500 BP). It remains unclear whether, during periods when humans were not present, the wetland also dried up. Periods of settlement hiatus are generally correlated with less modelled water availability, but because our model cannot currently constrain the *minimum* plausible size of the wetland, nor its seasonal persistence, we cannot state this in stronger terms. A substantial permanent water body was always possible, but a series of smaller/seasonally-present water bodies are equally plausible. The lack of these lower bounds on our hydrological model is primarily because we lack data on the subsurface shape of the qa’ basin in relation to its outflow to Wadi Rajil, and subsequently cannot effectively model the volume of water it could retain. Further palaeoenvironmental work on the evolution of the qa’ basin and its sediment fill (Jones et al. 2022) could solve this problem.

We can further infer a number of fluctuations in potential availability from our combined palaeoclimate and hydrological modelling (fig. 6). It indicates temperatures slightly higher and effective precipitation just below the levels associated with the Early Holocene during the 15,000–14,000 BP time frame, alongside high reconstructed evaporation. This is predicted to have resulted in a higher proportion of the qa’s surface area being flooded. The model indicates that 20-25% of the qa’ could have been flooded year-round during this time. The models’ predictions coincide with a strong signal of human occupation at Shubayqa 1 during the Early Natufian between c. 14,600 and 14,000 BP. The archaeological settlement, zooarchaeological and archaeobotanical record indicates not only persistent settlement activity at Shubayqa 1 during the 14,600–14,000 BP time frame but also strongly supports the presence of a more extensive wetland ecosystem as suggested by the presence of migratory and breeding populations of different water-dependent bird species, as well as different aquatic plants.

After 14,000 BP the model predicts a sharp drop in precipitation, far below Early Holocene levels, while evaporation remains high. This results in a predicted reduction of inflow to the qa’ to its lowest level in the period modelled. This was unexpected, as it does not conform with current paleoenvironmental data for the Bølling-Allerød in the region. Data from

Azraq, for instance, suggests recharged groundwater and higher lake levels during this period (Jones and Richter 2011), although in Azraq this may be due to prior climatic conditions, is it takes time for water to move through the aquifer. Other paleoenvironmental data also point to higher precipitation and warm conditions at this time (Jones et al., 2019).

An abrupt break in radiocarbon dates after 14,000 BP until 13,300 BP at Shubayqa 1 suggests a lack of human occupation or activity at the site that coincides with this sharp drop in inflow and flooding. The radiocarbon dates from Shubayqa 1 do indicate a re-occupation of the site between c. 13,300 and 13,000 BP – just before a sharp increase in mean annual precipitation in the model just before 13,000 BP. Zooarchaeological data again suggests the presence of migrating and breeding populations of various water-reliant bird species, whereas the archaeobotanic data provides a contrasting picture, where wetland (e.g. clubrush) plants are present, but not a significant number of aquatics. This suggests that the local wetland was undergoing a recovery process at this stage, and that plant communities had not yet fully recovered to full wetland conditions.

The onset of the Younger Dryas is marked by a predicted increase in inflow to the qa', coupled with very low evaporation—lower than the Early Holocene—and a corresponding predicted expansion of wetlands. The Younger Dryas overall is not predicted to have been an especially challenging period in our model. Curiously, present archaeological data is absent between 13,100 and 12,000 BP. At face value this would indicate lack of occupational activity in the Qa' Shubayqa in this period even though local conditions are predicted to be favourable. There could be several explanations for this mismatch in model prediction and the archaeological signature: (a) the model is erroneous, (b) while Shubayqa 1 was not occupied during this time, occupation may have focused on another locality around the qa', which has not yet been excavated, or (c) the area was not occupied for other reasons. We believe that the most likely explanation for this data is that humans were likely inhabiting the Qa' Shubayqa during the entire Younger Dryas, but that this period is currently not represented in its entirety in the available data.

Human occupation is indicated again from c. 12,000 BP onwards at Shubayqa 1, Shubayqa 3 and Shubayqa 6 and continues at Shubayqa 6 until c. 10,600 BP, spanning the transition from the end of the Pleistocene into the Early Holocene. From c. 12,000 BP evaporation rates ameliorate to Holocene levels, but there is no significant change in either inflow into the qa' nor predicted size of the wetlands. The archaeological data suggests intensive settlement activity around the qa' at this time with Shubayqa 1, 3 and 6 all being occupied. There are also other, not yet radiometrically dated, site locations dotted around the edge of the qa' where material culture indicates occupation during the Late Pleistocene and Early Holocene, namely the Late Epipalaeolithic and the PPNA. Zooarchaeological and archaeobotanical evidence once more provide strong confirmation for the presence of water dependent animal and plant species, confirming the view gained from the paleo-climatic and hydrological models.

We must attach a number of important caveats to the above narrative. First, while the global climate model-based palaeoclimate simulations that we have relied upon here have the distinct advantage of producing continuous and regionally-specific reconstructions, they are still a single model. The level of predictive uncertainty or agreement with proxies used for calibration is difficult to assess without access to the internal experimental data, and here we have observed that the simulated palaeoclimate for southwest Asia departs significantly from previous proxy-based reconstructions. At present we have no ready explanation for this misalignment, but parallel work on Europe suggests that it may be a general deficiency of global climate model-based palaeoclimate simulations (Traylor et al. 2025). Further work would therefore benefit from combining multiple simulations and explicitly re-calibrating them against regional palaeoclimate archives (though these are few and far between for the Badia). A second major caveat concerns the inherent logical problem in arguing from 'absence of evidence' in the archaeological record. This affects both our inference of settlement history and the reconstruction of the environment from archaeological evidence. At present our knowledge of both is based on full excavations at just two sites and, to a lesser extent, sondages at six others. We know that there are many more potential Epipalaeolithic–Neolithic sites around the qa', and further excavations there could change the settlement and environmental story dramatically.

# 6 Conclusion

Our findings emphasise that human resilience to climate change begins with the environmental system itself. Both hydrological modelling and archaeological evidence strongly indicate that, despite being a period of significant global climate change, there existed a stable wetland ecosystem at Shubayqa throughout the Pleistocene–Holocene transition. This environment enabled human communities to maintain substantial, long-lived settlements in an otherwise marginal dryland for the best part of five thousand years. Deglaciation is modelled to have brought a c. 200 mm increase in annual precipitation and 1.5 °C increase in average temperature at Shubayqa, but it does not appear to have been associated with a qualitative shift in weather patterns, the disappearance of its wetland ecosystem, or significant changes in the trajectory of human settlement. The cooler temperatures of the Younger Dryas period (12,900 to 11,700 BP), to which many have attributed a disproportionate impact on human social evolution in southwest Asia and beyond (Eren 2012), do not appear to have significantly affected the hydrological system at Shubayqa, as they were mitigated by a simultaneous increase in rainfall. These results caution us against grand visions of environmental change in prehistory and straightforward correlations between global climate and human society.

Where our models do indicate a possible human response to climate change, is it is not a straightforward story of 'ameliorated' climate bringing more people. Water is an obvious prerequisite for human life in this arid environment and, indeed, the initial occupation of the qa' neatly coincides with a major spike in predicted water availability around 14,500 BP. We have no evidence of human occupation of the qa' before this time—despite extensive archaeological survey—which suggests that some threshold of survivability and/or taphonomic preservation was in fact crossed. The subsequent dry period between 14,000 BP and 13,000, and the apparent settlement hiatus associated with it, strengthens this interpretation. At this point, however, two observations interrupt the linear narrative. Two isolated radiocarbon dates from Shubayqa 1 at c. 13,300–13,000 BP show that there was some form of human presence at the qa' even at the most severe point of this dry period. Second, the resumption of continuous settlement of the qa' did not happen with the return of wet conditions c. 13,000 BP, but rather a thousand years later. Here we are reminded that nonequilibrium ecosystems in general (Phillips 2004; Briske et al. 2017), and desert wetlands in particular (Ramsey 2023), are prone to non-reversible state changes in response to environmental perturbations. One way to explain the apparent non-linear human response to climate change at Shubayqa is therefore that, if a drop in precipitation caused a state change in the wetland that made it inhospitable to human settlement, the return of the previous rainfall regime would not necessarily restore the prior state of the wetland. But a more detailed and continuous picture of the qa's ecosystem through time is needed to test this hypothesis.

The nonlinear relationship between water availability and human settlement at Shubayqa highlights the ambiguity of the resilience paradigm and the difficulty in robustly applying it to prehistory. At face value, the apparent abandonment of the qa' in the driest periods suggests that human communities at Shubayqa were not especially resilient to climate change; they were not able to formulate technological responses or other adaptive strategies that allowed them to remain there. At the same time, it is possible (if not probable) that they simply relocated somewhere else. In this scenario, the flexibility of the broader meta-population of the Badia in deserting Shubayqa when it did not retain enough water, and rapidly recolonising it when it did, can be readily seen as a resilience strategy. On a broader level, the presence of *any* prehistoric occupation at Shubayqa—a location on the very edge of the 'climatic envelope' of human habitability today (Xu et al. 2020)—and its relative stability over five thousand years of the most rapid climate change in our species' premodern history, is itself remarkable. We are left with a paradox: if the same trend in human–environment interaction, depending on the scale we look at it, can be seen as both resilience and non-resilience, is it a phenomenon that is truly detectable in the archaeological record?

# Data Availability

The data and R code used for hydrological modelling can be obtained via Zenodo at https://doi.org/10.5281/zenodo.17482936.

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