

The domestication of water: water management in the ancient world and its prehistoric origins in the Jordan Valley

BY STEVEN MITHEN*

*Faculty of Science, University of Reading, Whiteknights, PO Box 220,
Reading RG6 6AF, UK*

The ancient civilizations were dependent upon sophisticated systems of water management. The hydraulic engineering works found in ancient Angkor (ninth to thirteenth century AD), the Aztec city of Tenochtitlan (thirteenth to fifteenth century AD), Byzantine Constantinople (fourth to sixth century AD) and Nabatean Petra (sixth century BC to AD 106) are particularly striking because each of these is in localities of the world that are once again facing a water crisis. Without water management, such ancient cities would never have emerged, nor would the urban communities and towns from which they developed. Indeed, the ‘domestication’ of water marked a key turning point in the cultural trajectory of each region of the world where state societies developed. This is illustrated by examining the prehistory of water management in the Jordan Valley, identifying the later Neolithic (approx. 8300–6500 years ago) as a key period when significant investment in water management occurred, laying the foundation for the development of the first urban communities of the Early Bronze Age.

Keywords: water management; Jordan Valley; Neolithic; urban; domestication of water; water crisis

1. Introduction

The planet is facing a water crisis: one billion people do not have access to safe drinking water. Two billion people have inadequate sanitation. By 2025, almost one-fifth of the global population are likely to be living in countries or regions with absolute water scarcity, whereas two-thirds of the population will most probably live under conditions of water stress (UN Water 2007). Excessive extractions of groundwater are causing rivers to run dry and wetlands to shrink; freshwater supplies and oceans are becoming polluted. Throughout the world, political tension is rife within and between countries regarding access to precious and dwindling water supplies, tensions that hinder peace processes and threaten to erupt into armed conflict (Gleick 2006; Barlow 2007). Population growth, economic development and urbanization place unrelenting pressure on the planet’s water resources. On-going, human-induced, climatic change is likely to

*s.j.mithen@reading.ac.uk

One contribution of 14 to a Discussion Meeting Issue ‘Water and society: past, present and future’.

have a further detrimental impact on water supplies to large sectors of the global population: precipitation is forecast to decrease and evaporation to increase in precisely those areas that are already suffering from water stress (IPCC 2007; UNEP 2007).

How did we get into this mess? How will we get out of it?

2. Water: the cause of the water crisis

If the second question is one for all of us to address, the first is primarily one for those who study the past and can be addressed at a variety of time scales. If one adopts a long-term perspective, starting with the emergence of *Homo* more than two million years ago, the answer as to how our water crisis has arisen is quite simple: by water itself. Or to be more accurate, not water but what people have done with water ever since our ancestors evolved on the African savannah. We have done just two things.

First, water has been domesticated. By this, I mean that its natural properties have been constrained and manipulated to cater for human need, whether in terms of a few drops being carried within a cupped-leaf by *Homo habilis* two million years ago or by the astonishing hydraulic engineering works that pervaded the ancient world. It was the domestication of water that enabled the consolidation and spread of farming lifestyles that ignited the exponential population growth that has occurred since the Neolithic times more than 10 000 years ago. It was the domestication of water that allowed urban centres to develop, whether we mean the Bronze Age site of Bab el Dra in the Jordan Valley or modern-day Tokyo, presently the largest city in the world.

Second, water has been transformed. The transformation of water into steam powered the industrial revolution that led to the step change in greenhouse gas emissions, which are now contributing to the climatic change that will exacerbate the water crisis, ultimately caused by water's own domestication.

3. The archaeological study of water management

Archaeologists have long appreciated the importance of water management. Grahame Clark, the distinguished prehistorian, identified its key role in human history as long ago as 1944, writing a seminal article entitled 'Water in antiquity' (Clark 1944), which reviewed the available archaeological evidence. His penultimate sentence remains pertinent for our increasingly water-stressed twenty-first century world in which poverty and social inequality are pervasive in both the global north and south: 'So, from the stone age to the 20th century', Clark wrote, 'water has reflected the image of society'.

Clark was a master of the Grand Narrative (e.g. Clark 1977), and it is unfortunate that his article never formed the basis of a lengthier study of water management in antiquity. It was in the next decade, the 1950s, that water management and its relationship to society became the subject not of a Grand Narrative but of a Grand Theory. In Karl Wittfogel's monumental 1957 volume entitled *Oriental despotism: a comparative study of total power*, he forwarded the

view that state societies in Asia depended on the building of large-scale irrigation works—his so-called hydraulic hypothesis. This proposed that irrigation required organized, forced labour and a large and complex bureaucracy, both of which provided the basis for despotic rule (Wittfogel 1957).

The anthropologist Julian Steward made a similar argument in his 1955 volume *Irrigation civilisation*, claiming that irrigation was the catalyst for state formation (Steward 1955). These were grand theories relating water to society, the type of theories that we shy away from today. They have indeed been found wanting. Adams (1966, 1978) attempted to test the hydraulic hypothesis with regard to the rise of Mesopotamian civilization and found that complex systems of canals and irrigation came after the appearance of cities and the indicators of bureaucratic statehood, rather than before as Wittfogel had proposed. The same was found with regard to the emergence of the Mesoamerican archaic state (Scarborough 2003).

Moreover, it soon became evident that societies throughout history have developed sophisticated techniques of water management but did not evolve into states and that some of the most complex water management systems concerned reservoir management rather than irrigation. Indeed what has emerged during the last few decades of archaeological research is a far more complex and diverse association between water and society than Wittfogel, Steward, Clark or anyone else had ever imagined, one that defeats the construction of a single grand theory. Cross-cultural studies now emphasize the astonishing variety of methods of water management and the even greater variety of relationships to land, labour and power (Scarborough 2003).

When our academic concerns are dominated by seeking to understand the current water crisis and the potential impact of future climate change, it is worth reminding ourselves of how water management was indeed central to the past civilizations and the diversity of forms this took. To do so, I will look briefly at four centres of the ancient world.

4. Water management in the ancient world

(a) *Cambodia and Khmer Angkor*

The tourists who visit the freshwater lake of Tonle Sap in Cambodia to see the floating villages gain the impression of a watery paradise. But Cambodia is reported as being in the midst of a water crisis (Sharp 2008): Tonle Sap is argued to be polluted, with dwindling fish stocks and a falling water level. The communities of Tonle Sap suffer from water-related tensions and conflict (Keskinen *et al.* 2007). More generally, millions of people within Cambodia lack basic sanitation—access to latrines and clean water for drinking and washing. Ironically, they live amidst the hidden ruins of a society that had developed one of the most grandiose and effective systems of water management ever devised.

Angkor was the seat of the Khmer empire that flourished between the ninth and thirteenth centuries AD (Coe 2003). The ruins of the city, now located amidst forest and farmland, contain more than 1000 temples including Angkor Wat, said to be the world's largest religious monument. Angkor has the distinction of being the largest known pre-industrial city, its urban sprawl covering more

than 3000 km² and its population estimated to have been over one million. As such, it faced two water issues: how to protect itself from the monsoon rains between May and November and how to irrigate its agricultural land to feed such a population. The answer was a remarkable network of reservoirs, channels and embankments that in the 1950s, when the ruins of the city were first being systematically mapped by Bernard Phillip Groslier, led to it being designated as the ‘hydraulic city’ (Fletcher *et al.* 2008).

The remarkable water network of Angkor has recently been described by Fletcher *et al.* (2008). The channels and embankments were built from a combination of masonry and huge quantities of clayey sand, the readily available bulk building material on the Angkor plain. The banks of the channels served as roads, while people lived along the embankments and on occupation mounds. Shrines and water tanks were pervasive throughout the urbanized area. At the centre of this network were vast reservoirs. That known as the West Baray is claimed to be the largest single artefact created prior to the mid-nineteenth century, being 8 km long, 2 km across and able to hold 50 million litres of water.

The whole network has recently been mapped with the aid of space-borne radar images, some having been taken from the space shuttle Endeavour. A programme of excavation is underway by teams from the Cambodian Government and the University of Sydney, Australia, to understand how it functioned. It appears that there was a tripartite structure to the system. The northern zone collected water and then directed it towards the central area, feeding the massive reservoirs and temple moats. In this region at least, and most likely throughout the network, water evidently had a ritual function as well as being a source of drinking water and irrigation. When the West Baray was constructed in the eleventh century, an exquisite water court temple was built, which contained a 6 m long reclining bronze statue of Vishnu. When excessive amounts of water accumulated in the central region, it was dispersed and distributed via the channels of the southern zone, some taking water into the Tonle Sap Lake whereas other water ran along channels for more than 40 km, into the agricultural landscape.

This water management system evolved over three centuries, during which there was considerable remodelling, while major channel down-cutting occurred in the northern region and severe sedimentation in the south. Ultimately, the system could not be sustained. The attempt to feed a population of over one million led to extensive deforestation, top soil degradation and erosion. Such effects may have been exacerbated by a prolonged drought between 1413 and 1439, recently identified within tree rings by Brendan Buckley and his co-workers at Columbia University (Buckley *et al.* 2010). The environmentally destabilized city was then toppled by the armed forces of the Siamese and Chem from Vietnam. So those people in the vicinity of Tole Sap Lake today, people in so desperate need of fresh water, live within and above the ruins of one of the greatest water management systems any society has ever devised.

(b) Modern-day Mexico City and Aztec Tenochtitlan

An equally striking contrast between the present and the past can be found on the other side of the world at Mexico City. With a population of 20 million, this is the largest city in the western hemisphere, one facing a severe water crisis caused by overconsumption of a dwindling and contaminated supply. Less than

10 per cent of Mexico City's water is recycled, whereas more than 4 per cent of fresh water is lost through leaking pipes; the city and country are rife with social and political tension arising from the piping of water from the Mazahuas indigenous community 100 km from the city and from sale of bottled water for votes by political parties. Mexico City itself is sinking by 10 cm per annum into the old lake bed on which it is built as water is continuously pumped from wells (Barlow 2007).

That old lake bed into which the city is sinking tells a story. Rewind 700 years and the lake bed is replete with the waters of Lake Texcoco within which the Aztec city of Tenochtitlan is located on an island. Estimated to have had a population of 200 000 people (Smith 2005), it was favourably compared with Paris, Venice and Constantinople by the Spanish Conquistadors when they arrived on 8 November 1519. They found a city that was interlaced with canals, connected to the mainland by a causeway and which had a 16 km levee designed to keep spring-fed fresh water in the vicinity of the city separate from the brackish waters of the lake (Scarborough 2003). This was the largest of the three cities that formed the triple alliance, also known as the Aztec empire that had flourished since its foundation in 1325. Drinking water was brought from springs to the city by two aqueducts, each more than 4 km long and made of terracotta. To feed the population, the Aztecs had invented chinampas or floating gardens (Sanders *et al.* 1979; Arco & Ebrams 2008). All of the swampy areas of the lake had been converted into land suitable for cultivation by piling mud onto reed foundations, which were stabilized by weaving more reeds to function as walls and by planting trees at the corners of the plots. The Conquistadors found more than 30 000 acres of such chinampas growing maize, avocados, beans, tomatoes and chillis. So it was by a sophisticated system of water management to provide drinking water to the city and land for cultivation that had provided the basis for the Aztec civilization, one crushed by the Conquistadors. Its remains now lie buried below the modern-day buildings of Mexico City—a city that could certainly benefit from a resurrection of Tlaloc, the Aztec god of rain.

(c) Modern-day Istanbul and Byzantine Constantinople

Istanbul is rather smaller than Mexico City with a population of a mere 12 million, but nevertheless, one of the largest 25 cities in the world. Istanbul's water supply is certainly under stress, and the city's water authorities—the ISKI (Istanbul Water and Sewerage Administration)—predict that a crisis situation could arise by 2030 on the basis of projected increase in demand and reduced supply using the IPCC's 2°C temperature increase scenario. Major infrastructure investment is underway to enhance water supply, storage and recycling, including projects to transfer water to Istanbul from as much as 150 km away. Well, that has been done before and one cannot help but find profound parallels between the present and the past: between what the current authorities of Istanbul are undertaking to supply the city with water and what was done by the Byzantine rulers of Constantinople 1700 years ago.

It has long been known that Byzantine Constantinople (fourth to sixth centuries AD) had a sophisticated and complex water supply system, just as was the case for all major cities of the Roman and Byzantine worlds. But, recent research led by Jim Crow of the University of Edinburgh has shown that the

scale of Byzantine hydraulic engineering in the city was even more remarkable than the references within documents from antiquity and previous archaeological work had led us to believe (Crow *et al.* 2008). Unlike Rome, Constantinople, the new Imperial city, lacked a good water supply and had to bring this into the city from surrounding countryside. It did so by a series of channels, tunnels and aqueducts into a vast number of reservoirs and cisterns. The most astonishing of these is that which carried water from the springs and aquifers at Vize, 120 km in a straight line from Constantinople but which required a sinuous channel of 551 km long, the longest single supply line known from the ancient world. This required more than 30 stone bridges and many kilometres of underground tunnels to bring water right to the heart of the city. Many of these bridges are astonishing feats of engineering in themselves, such as the Kursunlugerme acknowledged by being decorated with Christian iconography, and the Bozdogan Kemer within the city. As Crow has explained, the completion of this water supply system in AD 373 inaugurated and confirmed Constantinople as the new capital of the Roman world. It supplied not only reservoirs for agricultural use and the cisterns for drinking water, but also the Imperial baths and fountain displays, an ostentatious waste of water being a requirement of any classical metropolis.

It is tempting to continue this global tour of the ancient world and look at the hydraulic engineering achievements of, say, Mycenaean Greece, the Harappan civilization of the Indus Valley, the Incas and the Mayan civilization—all of their cultural achievements having been based on sophisticated and extremely costly water management systems. But I will provide just one further example, one that takes us to southwest Asia and more specifically the Jordan Valley, an area of principal interest for the articles within this issue: the ancient city of Petra.

(d) *Nabatean water management at Petra*

Jordan is characterized as a ‘water-scarce’ country (Winpenny 2000). It has ambitious plans for monumental scale engineering works to bring water from the Disy aquifer that Jordan shares with Saudi Arabia to Amman and from the Red Sea to the Dead Sea in a joint plan with Israel and the Palestinian Authority (Beyth 2007). Those planning such works could take inspiration—or perhaps a warning—from the hydraulic engineering that occurred more than 2000 years ago at Petra.

Located within a valley in the south of Jordan, surrounded by mountains and sandstone ridges, this ancient city with its rock-cut tombs and temples is truly one of the most astounding and evocative sites of the ancient world. Petra was the capital of the Nabatean state, founded in 300 BC and annexed into the Roman Empire in AD 106. Located at the centre of major caravan routes linking east and west, it was the hub of a vast trading network that resulted in astounding wealth. At its peak, more than 30 000 people lived within the city—all thriving within a region receiving less than 10 cm of rain per annum. This was achieved by a remarkable system of channels, tunnels, dams, cisterns, aqueducts and reservoirs that captured every drop of rain and spring water (Ortloff 2005). The Nabateans perfected bottle-shaped cisterns cut into solid rock to minimize evaporation and the risk of pollution; they created plasters to line such constructions, which were resistant to percolation and the corrosive effects of water. It was by astonishing

feats of hydraulic engineering that large populations could be sustained not only within Petra itself but also throughout the deserts of the Nabatean kingdom (Oleson 2007).

A recent excavation in Petra has shown that water displays were used as an extravagant symbol of Nabatean wealth and power (Bedal 2003). What had been thought to be a market place tucked behind one of Petra's great temples turned out to be a monumental pool quarried out of bedrock with a 16 m vertical sandstone rock face as a backdrop. This had held over two million litres of water and had a central stone island on which there had been an ornate, brightly painted pavilion. From there, panoramic views were gained of not only the waters and surrounding sandstone cliff but also extravagant gardens with lush vegetation that surrounded the pool. Remember that Petra is located in the middle of an arid desert: imagine the impact on travellers and traders entering the city via its narrow siq: initially enthralled by the monumental rock-cut architecture, just as tourists are today, they would have been entirely overwhelmed by the sight of a watery paradise, an affirmation of the power of the Nabatean kings over nature.

The thousands of modern-day tourists who flock to Petra today place additional pressures on a region that is already suffering severe water shortages from the demands of agriculture and industry. Indeed, it is within the Middle East that the complex interplay between not only water and economic development but also with politics and identity is most apparent. Everyone agrees that the Middle East Water Question can only be addressed by paying attention to the post-war history of the region (Allan 2001)—without that nothing about the present can be understood or progress made. But I now want to take us further back in time to explore the long-term history of water and society, seeking to justify my initial claim that the management of water was essential to the development of farming and urban communities, those which laid the basis for the Nabatean civilization and the hydraulic engineering achievements of Petra.

5. Domestication of water in the Jordan Valley

Here I will draw on some of the research within the University of Reading's, Water, Life and Civilisation project, funded by the Leverhulme Trust between 2005 and 2010 (www.waterlifecivilisation.org; Mithen & Black in press). This has taken a fresh look at some of the prehistoric archaeology in the Jordan Valley, Wadi Araba and surrounding regions, by integrating archaeological study with that of palaeoclimatic and hydrological modelling (figure 1). I will also describe some recent archaeological discoveries that have thrown new light on our understanding of when and how water was first domesticated and the significance of this for the long-term evolution of society (for a detailed review of the archaeological evidence, see Finlayson *et al.* in press). The locations of sites referred to in the text are found in figure 2.

(a) Climate and colonization

The first human occupation in the Jordan Valley dates to more than 1.5 million years ago, as known from sites such as 'Ubediya (Stekelis 1966; Bar-Yosef & Tchernov 1972; Bar-Yosef & Goren-Inbar 1993). This was by *Homo ergaster* that had dispersed from Africa, that dispersal itself being a consequence of changing

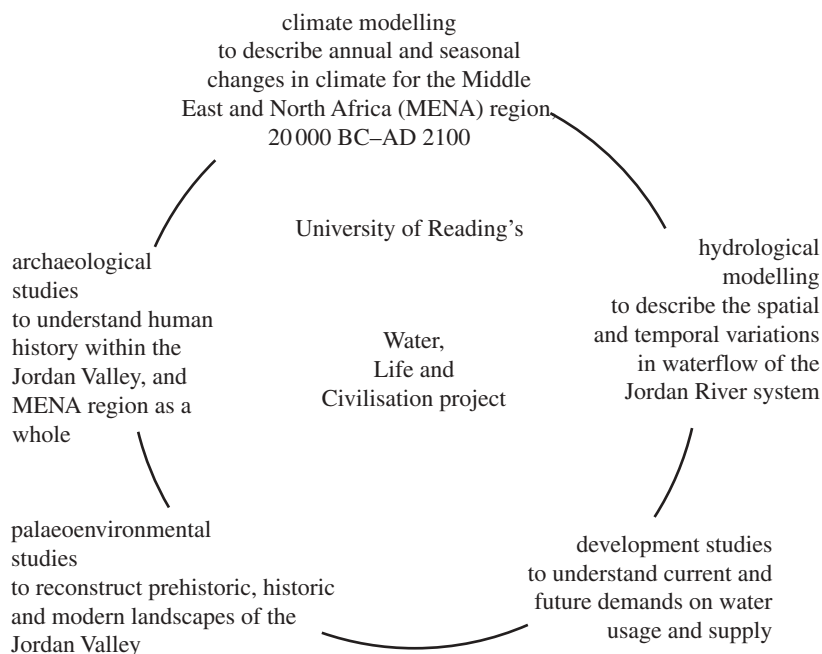


Figure 1. The Water, Life and Civilisation project, University of Reading, 2005–2010.

water availability caused by Pleistocene climatic change (Por 2004). From the time of the first settlement to at least the establishment of permanent farming villages at around 10 000 years ago, and probably for some time afterwards, people moved themselves to water rather than manipulated the passage of water within the landscape for their own needs—other than carrying water for personal need in skin containers and other vessels. So the temporary camping sites of the Neanderthals that arrived in the Jordan Valley at around 250 000 years ago and then the first modern humans as from 40 000 years ago were located adjacent to springs and lakes, allowing access to fresh water.

The site of Ohalo II, located on the shore of Lake Tiberias—the Sea of Gallilee—is our best example of a hunter–gatherer campsite dating to the late Pleistocene, specifically to 19 000 years ago (Nadel & Hershkovitz 1991; Nadel *et al.* 1995; Nadel & Werker 1999; figure 3). This was discovered and excavated during the drought years of 1989 and 1999 when the lake waters fell to expose the trace of dwellings on the shoreline, the excavation of which provided abundant evidence for the hunting of gazelle, the collecting of many plant foods including wild barley and fishing within the lake. It is surely no coincidence that this site is adjacent to a permanent water source. Elsewhere, the vast accumulations of debris at locations such as Kharaneh IV in Wadi Jilat must have been at least dependent on seasonally abundant water, perhaps attracting large social aggregations (Maher *in press*).

The extent of the lakes, most notably Lake Lisan, the remnants of which would become the Dead Sea, along with the flow of the rivers and springs on which the hunter–gatherers depended would have varied considerably during the

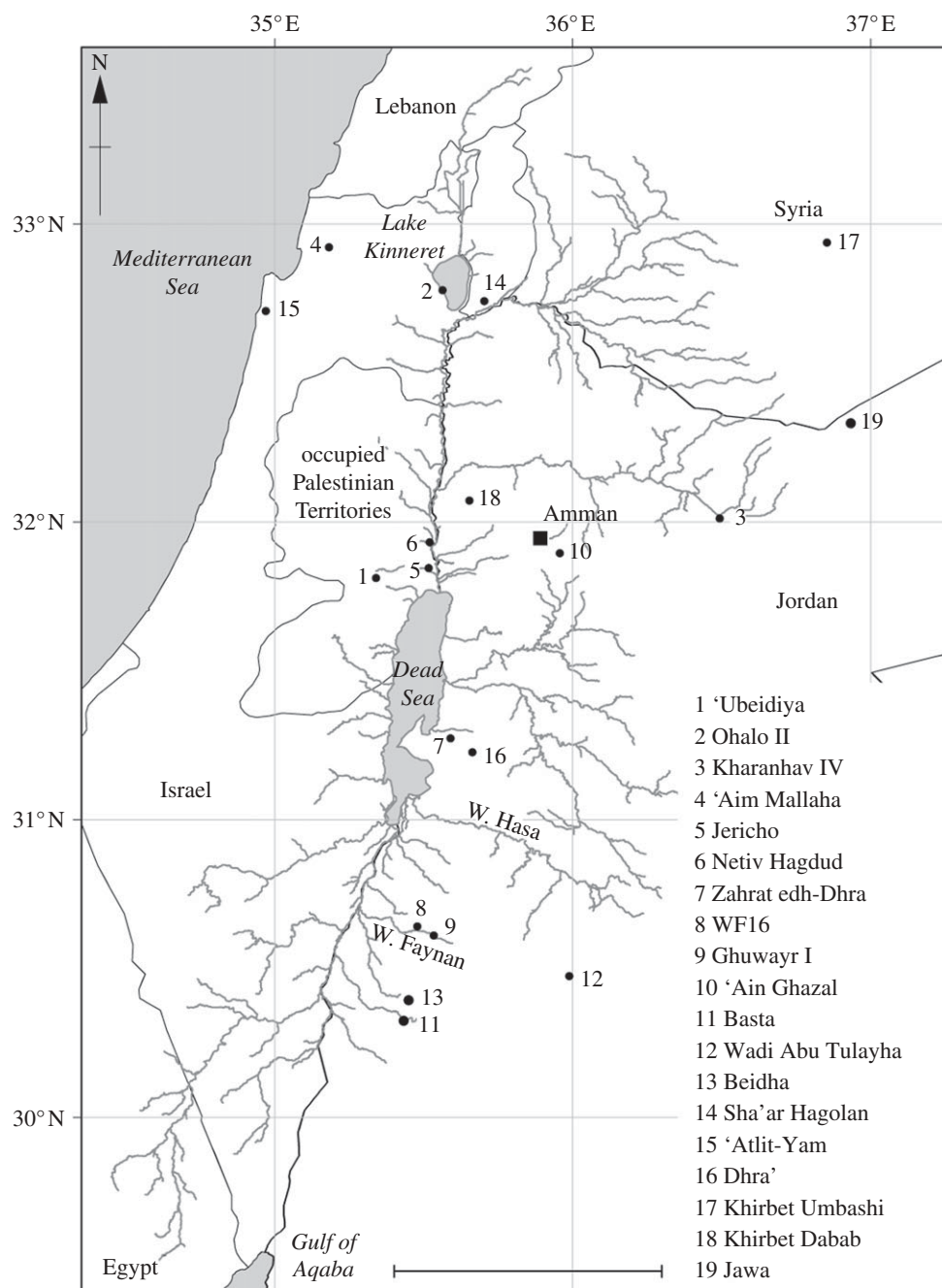


Figure 2. Map showing archaeological sites referred to in the text. Scale bar, 100 km.

next 10 000 years, during the periods of the late glacial interstadial and then the Younger Dryas, the period of the Natufian culture (Robinson *et al.* 2006; Black *et al.* in press). Archaeologists have been able to document some of the changes in lifestyles during this period, most notably the emergence of large, more complex



Figure 3. Remnant of brushwood hut at Ohalo II, showing location adjacent to Lake Tiberias.
Copyright © S. Mithen.

hunter–gatherer communities with art and architecture during the interstadial and the return to small, more mobile communities during the more arid conditions of the Younger Dryas (Mithen 2003). But, all such hunter–gatherers were tied to the natural distribution of water. The early Natufian site of Ain Mallaha dating to 14 500 years ago is a typical example (Valla *et al.* 1999). Here people built their dwellings and buried their dead close to a spring, after which the site is named, a spring that not only provided water to drink but also because of its stable temperature throughout the year attracted fish unable to cope with winter temperature elsewhere, and migrating birds (Por 2004).

(b) *Water supply and the Neolithic transition*

It is in the Early Holocene that the picture becomes more interesting with regard to water. The dramatic global warming at 11 600 years ago appears to have been the trigger for the development of sedentary and then farming communities, following the domestication of first cereals and pulses and then animals—sheep, goat and cattle (Mithen 2003). This is the Neolithic transition, once called a revolution (Childe 1936). The first stages are marked by settlements that are classified as those of the Pre-Pottery Neolithic A culture—normally abbreviated to the PPNA—that existed between 11 600 and 10 200 years ago (Bar-Yosef 1989; Kuijt & Goring-Morris 2002). Although the precise climatic conditions of this period will always remain elusive, the palaeoclimatic modelling undertaken by David Brayshaw and his co-workers within the Water, Life and Civilisation project has shown that the present-day temporal dynamics of winter rainfall and summer drought are also applicable to the Early Holocene (Brayshaw *et al.* in press).

The first PPNA settlement ever discovered was at the base of Tell-el Sultan at Jericho, found by Kathleen Kenyon during her excavations in the 1950s (Kenyon 1981). Since that date, numerous PPNA settlements have been excavated on the West Bank, such as Netiv Hagdud (Bar-Yosef & Gopher 1997) and Gilgal (Noy 1989), and then further south in Jordan such as Zahrat edh-Dhra' (Edwards & Higham 2001) and Dhra' (Finlayson *et al.* 2003). These have shown that this



Figure 4. Wadi Faynan, southern Jordan, showing location of PPNA site of WF16 and PPNB site of Ghuwayr I. Copyright © S. Mithen.

period of a little over 1000 years is the critical period of transformation from hunter–gatherer to farming lifestyles (Kuijt & Goring-Morris 2002; Mithen 2003). All of these early Neolithic settlements are adjacent to permanent water courses or springs. For instance, the inhabitants of Neolithic Jericho depended on the artesian spring of Ain el Sultan and on the wetlands of the stream of Wadi Qelt; the inhabitants of Netiv Hagdud used the waters from the spring of Ain Duyuk and the wetlands of the nearby delta of the River Jordan, emptying into the Dead Sea at a considerably higher level than it is today (Por 2004).

A useful case study for exploring the relationship between Neolithic settlement and water supply is Wadi Faynan, located in southern Jordan. This has been subject to considerable archaeological and palaeoenvironmental research and hydrological modelling (Barker *et al.* 2007; Finlayson & Mithen 2007; Wade *et al.* in press). The PPNA site of WF16 is located at the base of the escarpment to the Jordanian plateau at the juncture between Wadi Ghuwayr and Faynan (Finlayson & Mithen 2007; figure 4). This settlement was occupied over the course of the first 1000 years of the Holocene, probably beginning as a seasonal campsite for mobile hunter–gatherers and ending as the permanent settlement of early farmers, although that has yet to be confirmed by ongoing excavations (figure 5). It was abandoned at around 10 200 years ago, and it is assumed that its people moved no more than 500 m further down the wadi where the settlement of Ghuwayr I is located (Simmons & Najjar 1996). As is evident with figure 6, the architecture is now quite different with rectangular, two-storey structures built out of stone.

Ghuwayr I is an example of the Pre-Pottery Neolithic B phase—the PPNB—that lasted between 10 200 and 8300 years ago (Kuijt & Goring-Morris 2002). Many sites with architecture similar to that of Ghuwayr I are known, both within the Jordan Valley itself and in the surrounding hills, such as Wadi Shu'eib (Simmons *et al.* 1989) and Beidha (Kirkbride 1966; Byrd 2005). During the latter phases of this period, numerous so-called PPNB ‘mega-sites’ develop along the



Figure 5. Excavations at WF16, April 2009, showing pise-walled, semi-subterranean buildings. Copyright © S. Mithen.



Figure 6. Free-standing, stone-walled PPNB buildings of Ghuwayr I. Permission and copyright © A. Simmons.

top edge of the Jordanian plateau such as Ain Ghazal (Rollefson 1989) and Basta (Gebel *et al.* 2006). The largest of these sites are estimated to have had populations of 2000 people.

With regard to water, the PPNA and PPNB settlements in Wadi Faynan—WF16 and Ghuwayr I—are positioned in a manner similar to that of Ohalo II—immediately adjacent to a permanent supply of water. This is not the case today, or at least the trickle of spring flow that comes down the wadi is not sufficient to sustain communities of the size suggested by the number of dwellings at WF16 and Ghuwayr I. But at 10 000 years ago, the archaeological remains from recent excavations of WF16 (Finlayson & Mithen 2007) and hydrological modelling



Figure 7. Reconstruction of Wadi Faynan at 10000 BP. Copyright © S. Mithen.

(Wade *et al.* in press) suggest that this locality had been a highly attractive niche containing a perennial stream within a landscape where water may have been otherwise scarce (figure 7). Indeed, it is striking that the survey throughout Wadi Faynan has failed to find any other trace of PPNA settlement, suggesting that people were very much tied to the accumulation of water at the juncture of the two wadis (Finlayson & Mithen 2007).

Although no evidence for water management has been found by the excavations at WF16 and Ghuwayr I, a caveat must be made that very subtle alterations to a wadi bed of the type that would leave no archaeological trace can create substantial accumulations of water, albeit for short periods of time—these being created by the present-day Bedouin. Similar transient constructions had been made by the Neolithic inhabitants of WF16 and Ghuwayr I to create temporary cisterns in the wadi floor, perhaps also making use of the steep walls of the canyon.

There have been extensive excavations of numerous PPNB sites in the Jordan Valley and immediately surrounding area, revealing houses, store rooms, public buildings and workshops (Kuijt & Goring-Morris 2002). PPNB material culture is rich and diverse, with many artefact types and items of assumed religious significance. But, with one exception that I will shortly describe, even in the very largest of these settlements, there have been no traces of water management: no rock-cut aqueducts, no dams, no field walls to control run-off, no wells and no cisterns. The large farming villages of the PPNB appear to have been as dependent on an unmodified natural landscape for their supply of water as was the tiny, temporary campsite of Ohalo II. These permanently settled farmers appear to have had a hunter-gatherer mentality about their world: they may have now gained control over plants and animals—cereals, pulses, sheep and goats—but water was left untamed.

(c) Water management in the Jafr Basin

The one exception comes from the extremely arid Jafr Basin in the far south of Jordan. Sumio Fujii from Kanazawa University, Japan, has been working within this region since 1997 and discovered numerous prehistoric settlements. Two of these appear to have structures dating to the PPNB period and designed to collect run-off water, making these the earliest traces of water management not just in southwest Asia but in the world.

The most notable are those within Wadi Abu Tulayha (Fujii 2007*a,b*, 2008). In 2001, Fujii discovered a small PPNB settlement that he describes as an ‘outpost’ (figure 8); his 2005 excavations showed that this had been used by people who cultivated cereals and pulses and herded sheep, probably occupying the outpost for a few months each year as part of a transhumant round. The final buildings within the complex have been dated to around 9500 years ago. Close to the settlement and located in the base of the wadi, there is a large, amorphous structure that Fujii has interpreted as cistern used to capture the wadi flow to provide drinking water for people and their animals (figure 9). His interpretation is based on the location and form of this structure, its depth—more than 2 m—and the absence of occupation deposits. It is a persuasive interpretation, as is Fujii’s argument that it dates to the earlier phase of the occupation that remains undated.

He calculates that this cistern could have held up to 60 m³ of water, sufficient for a few dozen people with their livestock staying at the outpost for about a month. Another structure was found about 100 m away: a V-shaped wall across the wadi that Fujii describes as a barrage (figure 10). Circumstantial evidence suggests that this is chronologically later than the cistern. Fujii suggests that the difficulty in emptying the cistern of silt every spring had led to its gradual disuse and the adoption of the barrage as an alternative water run-off management system. He argues that rather than creating a reservoir, the barrage would have enhanced infiltration into the ground and enabled the accumulation of sediment suitable for cultivation. Evidence for such cultivation comes not just from the cereals and pulses that Fujii excavated, but also from quern stones and pounders.

It seems unlikely that in PPNB times the annual precipitation by itself would have been sufficient to have allowed cultivation, as also suggested by the absence of PPNB sedentary settlements in the Jafr Basin. Therefore, Fujii argues that this barrage wall enabled a few hectares of fields along the winding course of the wadi to have been developed. Approximately 8 km away, a similar barrage wall was found across the floor of another wadi (Wadi Ruweishid; figure 11). This lacks any associated settlement, but distinctive artefacts within the walls and the absence of any other settlement in the immediate vicinity suggest that this is also PPNB in date, enabling basin-irrigated crop field or pasture within an extremely arid region.

The discoveries in the Jafr Basin may be replicated elsewhere in the Jordan Valley now that archaeologists know what to look for, but at present these so-called barrages are the exceptions rather than the rule. Indeed, what is most striking about the PPNB villages and towns throughout the Jordan Valley is the absence of water management systems: dams, cisterns, reservoirs, terrace walls, wells, aqueducts and so forth. Except in the Jafr Basin, they are all lacking. Now we must be cautious because, as I have already noted, the evidence may not

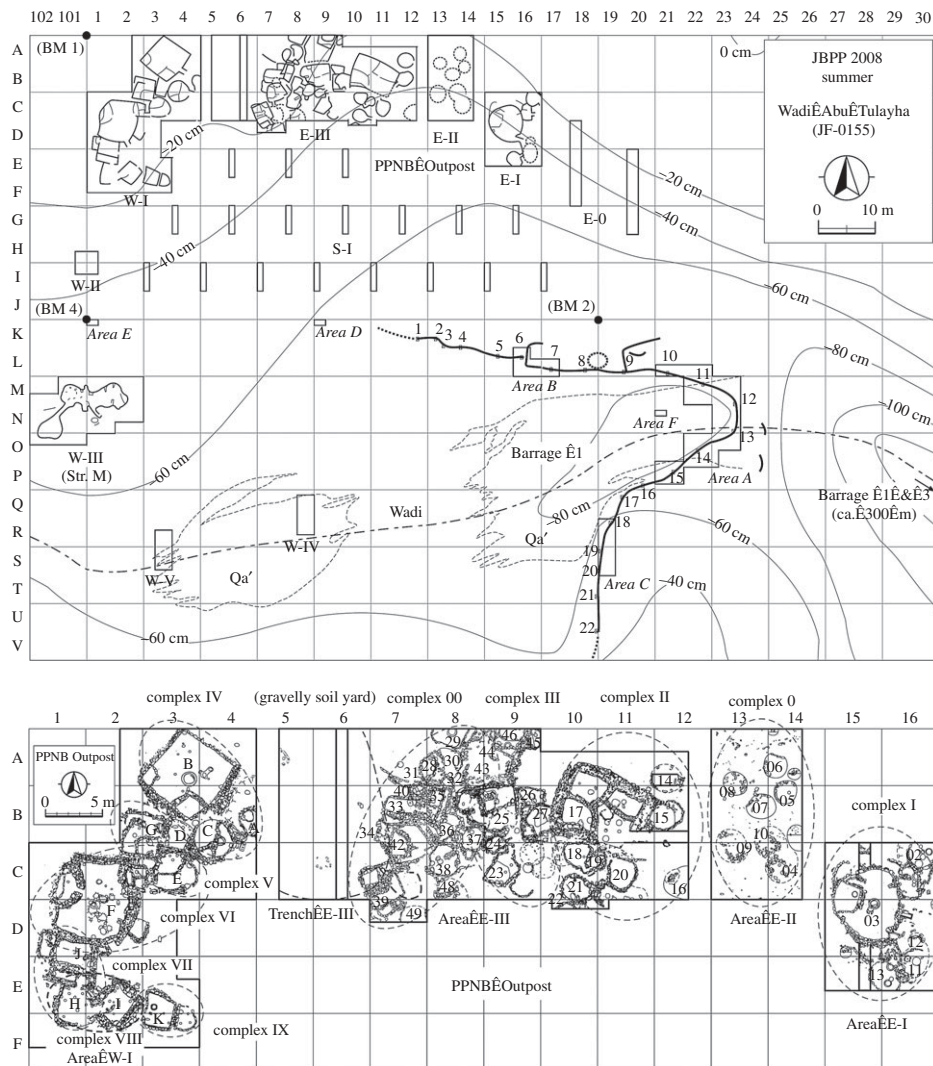


Figure 8. Plan of settlement and barrage at Wadi Abu Tulayha. Permission and copyright © S. Fujii.

survive. Moreover, archaeologists are prone to find only what they are looking for and PPNB hydraulic engineering has not been high on the agenda. But it does appear that these PPNB towns remained reliant on nature to provide their water needs.

(d) Water stress and collapse of the PPNB villages

The absence of water management systems may have contributed to their collapse: at around 8500 years ago, many of the PPNB villages and towns become abandoned, the settlement pattern shifting to a series of much smaller dispersed settlements, possibly reflecting the rise of nomadic pastoralism (Rollefson & Köhler-Rollefson 1989; Mithen 2003).



Figure 9. Cistern at Wadi Abu Tulayha. Permission and copyright © S. Fujii.



Figure 10. Barrage at Wadi Abu Tulayha. Permission and copyright © S. Fujii.



Figure 11. Barrage at Wadi Ruweishid. Permission and copyright © S. Fujii.



Figure 12. The PPNB settlement of Beidha, view from the southwest. Permission and copyright © C. Rambeau.

Beidha provides a good example (figure 12). This PPNB village was discovered and excavated by Dianne Kirkbride during the 1960s, providing one of the largest areas exposed of any such village (Kirkbride 1966). Below the PPNB remains are those of a hunter–gatherer settlement dating to the late glacial interstadial (Byrd 1989). The site is close to Petra and surrounding the PPNB village of Beidha are the many rock-cut aqueducts and cisterns of the Nabatean occupation of the area, showing the effort and skill with which the Nabateans had captured run-off water (Oleson 2007). In contrast, the Neolithic occupants of Beidha appear not to have engaged in any hydraulic engineering, choosing to rely on local springs, all of which have now ceased to flow. Rambeau, working within the Water, Life and Civilisation project, has located the travertine deposits left by one of these springs and used uranium series dating and isotope analysis to reconstruct the periods when the water had been flowing and to estimate local temperatures (Rambeau *et al.* in press). She has found a strong correlation between the flow of the water and occupation of the site: when the first ceased, as it did so during the Younger Dryas and then again at around 8500 years ago, so did the occupation at Beidha.

A similar history of continuing dependency on undomesticated water may have led to the abandonment of the PPNB settlement in Wadi Faynan, that of Ghuwayr I. Several hypotheses can be suggested: short-term climatic events that reduced the water entering the catchment; growth of human population exceeding what can be provided by an undomesticated water supply; and loss of vegetation cover that changed the dynamics of water flow. The potential significance of the third scenario has been explored within the Water, Life and Civilisation project at Reading. One of its aims has been to integrate palaeoclimatic and hydrological modelling to explore the environmental context of past human settlement. A major case study has been that of Wadi Faynan where the combination of expertise from archaeology (Smith), meteorology (Brayshaw and Black), hydrology (Wade) and geology (Rambeau) has produced an interdisciplinary model and interpretation of Early Holocene hydrology and its impact

on the local communities (Smith *et al.* in press; Wade *et al.* in press). This model has many implications for understanding the archaeology within Wadi Faynan, from the earliest prehistoric settlement to the Islamic occupation and indeed the present day. One of the key findings is the immense sensitivity of the hydrodynamics to the vegetation cover and hence water infiltration rate. When infiltration is relatively high, there is a substantial regular groundwater flow throughout the year and few, if any, flood events during the wet season—such floods have immense destructive power. Once a significant amount of the vegetation is removed, reducing infiltration, the same amount of water entering the catchment becomes distributed as a small trickle of groundwater and a series of massive winter floods.

Smith and co-workers suspect that this transition in the hydrodynamics of the Wadi did not occur until the Bronze Age and even the classical periods when massive vegetation removal occurred to feed the fires used for copper smelting in the Wadi (Barker *et al.* 2007). I suspect that it may have begun earlier in the Neolithic, caused by the foraging of goats and the collection of wood for building and fuel. Being without any means of water management, any such change in the hydrodynamics of the wadi may have been fatal for the inhabitants of Ghuwayr I, causing them to abandon their village.

Not all of the PPNB villages of the Jordan Valley become abandoned at around 8500 years. One with a continuity of occupation is prehistoric Jericho, situated close to a prodigious spring (Kenyon 1981). This site is unique in several respects, one of which is by having what appears to have been a town wall on its western side. Whereas Kenyon had originally interpreted this as a means of defence against human enemies, Bar-Yosef (1986) reinterpreted the walls in 1989 as a means of defence against mud flows. The type of modelling just described for Wadi Faynan supports this idea; the destabilization of soils may have been a pervasive problem throughout the Jordan Valley in the Neolithic.

(e) Water management in the Pottery Neolithic

Although some settlements show a long-term continuity of settlement, when taken as a whole, the Neolithic settlement pattern after 8500 years ago is transformed with the appearance of smaller and more dispersed sites, some now being located in parts of the landscape that suggest new forms of agricultural economies and relationships with water. In Wadi Faynan, for instance, the location of settlement shifts into the expansive area of the wadi bottom itself in the form of Tell Wadi Faynan (Najjar *et al.* 1990). Material culture is also transformed with the appearance of ceramics—we now enter the period of the Pottery Neolithic. It is also around this time, after 8500 years ago, when more substantial evidence for water management appears.

The most striking is found at the Neolithic site of Sha'ar Hagolan located in the northern reaches of the Jordan Valley: a well, dating to 8300 years ago, excavated by Garfinkel *et al.* (2006). This is not the earliest known well. This comes from the west coast of Cyprus where three Neolithic wells have been dated to approximately 10 000 years old (Peltenberg *et al.* 2000; Croft 2003). Three more Neolithic wells have been discovered from the underwater site of 'Atlit-Yam near the Mediterranean coast dating to around 9000 years ago (Galili & Nir 1993; Galili *et al.* 1993). That of Sha'ar Hagolan is the earliest known in the Jordan Valley.



Figure 13. The Pottery Neolithic settlement of Sha'ar Hagolan. Permission and copyright © Y. Garfinkle.

Sha'ar Hagolan is one of the largest known Neolithic settlements, covering 20 ha with streets and courtyard houses, giving the impression of a well-organized settlement (figure 13). The well appears to have been in an open area rather than within the courtyard of a private building. It consists of a 4.2 m shaft, the upper portion of which was stonelined, whereas the base widened out at the level of the water table (figure 14). The meticulous excavation has revealed the stages and methods of construction, along with the accumulation of sediment and domestic refuse after it had fallen into disuse.

One of the most intriguing features of the Sha'ar Hagolan well is that it was dug reasonably close to a permanent fresh water source, the Yarmuk River—the well was no more than a few tens of metres at most from the river bank itself. This is quite different from the location of the wells on Cyprus and at 'Atlit-Yam, which were evidently dug in locations of water shortage. So why dig the well at Sha'ar Hagolan? It may have been for convenience, to save that extra bit of effort that a trip to the river to fill vessels required. Alternatively, as Garfinkel and his co-workers have suggested, the well might have been dug to provide isolated water that was of guaranteed quality, the river being open to pollution by humans or animals. Another possibility—and one that I would favour—is that the well had functioned as a status symbol, perhaps the first evidence of water being used as a sign of wealth and power.

The settlement of Sha'ar Hagolan dates towards the end of the Neolithic period. Another water management structure has been dated to this time: the earliest terrace walls to inhibit soil erosion and maximize water use for a field system. This is at the Pottery Neolithic settlement of Dhra', located close to the Dead Sea. Excavations by Kuijt and his co-workers in 2005 revealed the presence of a suite of terrace walls close to a Pottery Neolithic settlement with rectangular buildings (Kuijt *et al.* 2007). Nine of these walls have been found between 100 and



Figure 14. The well at Sha'ar Hagolan. Permission and copyright © Y. Garfinkle.

200 m away from the buildings. They were oriented perpendicular to the slope and placed directly across bedrock outcrops as a means to anchor them against the flow of water (figure 15).

These walls, some of which had stood almost 1 m high and ran for more than 20 m, indicate a significant investment of labour into the construction and maintenance of field systems, the walls functioning to minimize soil erosion and to control run-off during wet periods of the year. The scatter of pottery and other refuse in the vicinity of the walls suggests attempts at manuring to fertilize the soil.

(f) *Water management in later prehistory of the Jordan Valley*

The Pottery Neolithic is followed by the Chalcolithic and then at around 5500 years ago by the Early Bronze Age, which marks the first appearance of urban centres. Space prevents me from following the developments regarding water management in any detail. Suffice to say that there is widespread agreement among archaeologists that this has now become central to the Chalcolithic economy: we move into a period in which water has been domesticated.

The growth of large settlements within flood plains such as Teleilat Ghassul suggests the use of irrigation by 6000 years ago (Bourke 2008). Hard evidence for such irrigation has remained elusive; it being primarily inferred through



Figure 15. Excavating remnants of the Pottery Neolithic terrace wall at Dhra'. Permission and copyright © B. Finlayson.

the presence of plant remains which would have required a managed water supply. Emma Jenkins working with the Water, Life and Civilisation project has been building on previous work that has used the size and structure of plant phytoliths as a means to infer the presence of past irrigation systems (Mithen *et al.* 2008; Jenkins *et al.* in press). At upland sites such as el Khawarji in the Wadi Rayyan, the excavations of Lovell *et al.* (2005, 2007) have found walls demarcating and controlling access to natural cavities within the rock that trapped the water table, while rock-cut channels collected water from surface run-off.

As we move into the Bronze Age after 5500 years ago, the archaeological evidence for water management becomes more substantial. Returning to Wadi Faynan once again, we find the steps towards constructing an extensive series of walls within the wadi bottom to collect run-off for crop irrigation, a system that becomes elaborated to sustain the Roman and Byzantine settlement (Barker *et al.* 2007). Bronze Age settlements are known to have rock-cut shafts and tunnels for water, reservoirs both within and outside their town walls and then from the Middle Bronze Age rock-cut cisterns (Ben-Tor 1992; Mabry *et al.* 1996; Philip 2008). Complex water management systems allowed desert landscapes to be colonized, as evident from the Early Bronze Age sites of the Harra, notably Khirbet Umbashi and Khirbet Dabab (Braemer *et al.* 2009). Jawa, now located on the Jordanian and Syrian border, has a complex system of canals and pools, which allowed winter rainfall to be collected and stored (Helms 1981). Paul Whitehead and others of the Water, Life and Civilisation project have used climate and hydrological models to explore how such Bronze Age hydraulic engineering could have sustained a population of 6000 people within a region of high aridity (Whitehead *et al.* 2008, in press).

With these Chalcolithic and Bronze Age developments that I have only briefly described, water had become fully domesticated within the Levant. As such, the constraint towards the development of fully urban communities, and ultimately the early civilizations, had been removed.

6. Conclusion

I began by emphasizing how the early civilizations were built on complex systems of water management and hydraulic engineering, the evidence for this being found in some of what are now the most water-stressed regions of the world: the plans and achievements of the rulers of Angkor, Tenochtitlan, Constantinople and Petra should serve as inspiration to those of Cambodia, Mexico City, Istanbul and Jordan today as they struggle with the present-day water crisis. I then chose the Jordan Valley and its vicinity to explore the history of water domestication and its relationship to the development of farming economies and ultimately urbanization in this particular region. We found that the earliest farming communities, those of the PPNA and PPNB, remained tied to natural sources of water and ultimately could not be sustained. It was only after the development of water management, which not surprisingly may have begun in the most marginal region of the Jafar Basin, that farming communities could grow into towns and ultimately urban centres. Ultimately, it was the domestication of water that allowed civilization to emerge.

I would like to thank all of my colleagues within the Water, Life and Civilisation project and the Leverhulme Trust for having provided the financial support. I am especially grateful to Emily Black for her contribution to the project as a whole and the development of my own knowledge and thought.

References

- Adams, R. 1966 *The evolution of urban society: early Mesopotamia and prehistoric Mexico*. Chicago, IL: Aldine.
- Adams, R. 1978 Strategies of maximization, stability and resilience in Mesopotamian society, settlement and agriculture. *Proc. Am. Phil. Soc.* **122**, 329–335.
- Allan, J. A. 2001 *The Middle East water question: hydropolitics and global economy*. London, UK: I. B. Tauris.
- Arco, L. J. & Abrams, E. M. 2008 An essay on energetic: the construction of the Aztec chinampa system. *Antiquity* **80**, 906–918.
- Barker, G., Gilbertson, D. & Mattingly, D. 2007 *Archaeology and desertification: the Wadi Faynan landscape survey, southern Jordan*. Levant Supplementary Series 6. Oxford, UK: Oxbow and CBRL.
- Barlow, M. 2007 *Blue covenant: the global water crisis and the coming battle for the rights to water*. New York, NY: The New Press.
- Bar-Yosef, O. 1986 The walls of Jericho: an alternative interpretation. *Curr. Anthropol.* **27**, 157–162. (doi:10.1086/203413)
- Bar-Yosef, O. 1989 The PPNA in the Levant, an overview. *Paléorient* **15**, 57–63.
- Bar-Yosef, O. & Gopher, A. (eds) 1997 *An early Neolithic village in the Jordan Valley. Part I: the archaeology of Netiv Hagdud*. Cambridge, UK: American School of Prehistoric Research, Peabody Museum.
- Bar-Yosef, O. & Goren-Inbar, N. 1993 *The lithic assemblages of 'Ubeidiya: a Lower Palaeolithic site in the Jordan Valley*. Qedem 24. Jerusalem: Institute of Archaeology, Hebrew University of Jerusalem.

- Bar-Yosef, O. & Techernov, E. 1972 *On the palaeo-ecological history of the site of 'Ubeidiya*. Jerusalem: Israel Academy of Sciences and Humanities.
- Bedal, L.-A. 2003 *The Petra pool complex: a Hellenistic paradeisos in the Nabataean capital*. Piscataway, NJ: Gorgias Press.
- Ben-Tor, A. 1992 The Early Bronze Age. In *The archaeology of ancient Israel* (ed. A. Ben-Tor), pp. 81–125. New Haven, CT: Yale University Press.
- Beyth, M. 2007 The Red Sea and the Mediterranean–Dead Sea canal project. *Desalination* **214**, 365–371. (doi:10.1016/j.desal.2007.06.002)
- Black, S., Robinson, S., Fittion, R., Goodship, R. & Rambeau, C. In press. Palaeoenvironmental and limnological reconstruction of the Dead Sea. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Bourke, S. 2008 The Chalcolithic. In *Jordan: a reader* (ed. R. Adams), pp. 109–160. London, UK: Equinox.
- Braemer, F., Genequand, D., Dumond Maridat, C., Blanc, P.-M., Dentzer, J.-M., Gazagne, D. & Wech, P. 2009 Long-term management of water in the Central Levant: the Hawran case (Syria). *World Archaeol.* **41**, 36–57. (doi:10.1080/00438240802666424)
- Brayshaw, D., Black, E., Hoskins, B. & Slingo, J. In press. Past climates of the Middle East. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Buckley, B. *et al.* 2010 Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc. Natl Acad. Sci. USA* **107**, 6748–6752. (doi:10.1073/pnas.0910827107)
- Byrd, B. F. 1989 *The Natufian encampment at Beidha: Late Pleistocene adaptations in the southern Levant*. Jutland Archaeological Society Publications, no. 23. Aarhus, Denmark: Aarhus University Press.
- Byrd, B. F. 2005 *Early village life at Beidha, Jordan: Neolithic spatial organization and vernacular architecture*. Oxford, UK: Oxford University Press.
- Childe, V. G. 1936 *Man makes himself*. London, UK: Watts.
- Clark, G. 1944 Water in antiquity. *Antiquity* **18**, 1–15.
- Clark, G. 1977 *World prehistory: a new outline*. Cambridge, UK: Cambridge University Press.
- Coe, M. 2003 *Angkor and the Khmer civilization*. London, UK: Thames & Hudson.
- Croft, P. 2003 The Cypro Pre-Pottery Neolithic B occupation: the wells and other vestiges. In *The colonisation and settlement of Cyprus. Investigations at Kissonerga-Myliouthkia 1976–1996* (ed. E. Peltenberg), pp. 3–11. Sävedalen, Sweden: Paul Astroms.
- Crow, J., Bardill, J. & Bayliss, R. 2008 *The water supply of ancient Constantinople*. Society for the Promotion of Roman Studies, Journal of Roman Studies Monograph no. 18.
- Edwards, P. C. & Higham, T. 2001 Zahrat adh-Dhra'2 and the Dead Sea Plain at the dawn of the Holocene. In *Australians uncovering ancient Jordan: 50 years of Middle Eastern archaeology* (ed. A. Walmsley), pp. 139–152. Sydney, Australia: University of Sydney.
- Finlayson, B. & Mithen, S. (eds) 2007 *The early prehistory of Wadi Faynan, Southern Jordan, archaeological survey of Wadis Faynan, Ghuwayr and al-Bustan and evaluation of the Pre-Pottery Neolithic A site of WF16*. Wadi Faynan Series 1, Levant Supplementary Series 4. Oxford, UK: Council for British Research in the Levant and Oxbow Books.
- Finlayson, B. *et al.* 2003 'Dhra' Excavation Project 2002. Interim report, Levant, 35, pp. 1–38.
- Finlayson, B., Lovell, J., Smith, S. & Mithen, S. J. In press. The archaeology of water management in the Jordan Valley 21 000 BP–AD 100. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Fletcher, R., Penny, D., Evans, D., Pottier, C., Barbetti, M., Kumm, M., Lustig, T. & Authority for the Protection and Management of Angkor and the Region of Siem Reap (APSARA) Department of Monuments and Archaeology Team. 2008 The water management network of Angkor, Cambodia. *Antiquity* **82**, 658–670.
- Fujii, S. 2007a Wadi Abu Tulayha: a preliminary report of the 2006 Summer Field Season of the Jafr Basin Prehistoric Project, Phase 2. *Annu. Dept Antiq. Jordan* **51**, 373–401.

- Fujii, S. 2007*b* PPNB barrage systems at Wadi Abu Tulayha and Wadi Ar-Ruwayshid Ash-Sharqi: a preliminary report of the 2006 Spring Field Season of the Jafr Basin Prehistoric Project, Phase 2. *Annu. Dept Antiq. Jordan* **51**, 403–427.
- Fujii, S. 2008 Wadi Abu Tulayha: a preliminary report of the Summer Field Season of the Jafr Basin Prehistoric Project, Phase 2. *Annu. Dept Antiq. Jordan* **52**, 445–478.
- Galili, E. & Nir, Y. 1993 The submerged Pre-Pottery Neolithic water well of Atlit-Yam, northern Israel and its palaeoenvironmental implications. *Holocene* **3**, 265–270. (doi:10.1177/095968369300300309)
- Galili, E., Weinstein-Evron, M., Hershkovitz, I., Gopher, A., Kislev, M., Lernau, O., Kolska-Horwitz, L. & Lernau, H. 1993 Atlit-Yam: a prehistoric site on the sea floor off the Israeli coast. *J. Field Archaeol.* **20**, 133–157. (doi:10.2307/529950)
- Garfinkel, Y., Vered, A. & Bar-Yosef, O. 2006 The domestication of water: the Neolithic well at Sha'ar Hagolan, Jordan Valley, Israel. *Antiquity* **80**, 686–696.
- Gebel, H. G. K., Nissen, H. J. & Zaid, Z. 2006 *Basta II: the architecture and stratigraphy*. Berlin, Germany: ex Oriente.
- Gleick, P. H. 2006 Water and terrorism. In *The world's water 2006–2007: the biennial report on freshwater resources* (ed. P. H. Gleick), pp. 1–28. Washington, DC: Island Press.
- Helms, S. 1981 *Jawa: lost city of the Black Desert*. London, UK: Methuen.
- IPCC. 2007 Impacts, adaptation and vulnerability. Working Group II, fourth assessment report. See <http://www.ipcc.ch/ipccreports/ar4-wg2.htm>.
- Jenkins, E., Jamjoum, K. & Nuimat, S. In press. Irrigation and phytolith formation: an experimental study. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Kenyon, K. M. 1981 *Excavations at Jericho, vol. III: the architecture and stratigraphy of the Tell*. London, UK: British School of Archaeology in Jerusalem.
- Keskinen, M., Kähkönen, K., Tola, P. & Varis, O. 2007 The Tonle Sap Lake, Cambodia: water-related conflicts with abundance of water. *J. Peace Security* **2**, 49–59.
- Kirkbride, D. 1966 Five seasons at the Pre-Pottery Neolithic village of Beidha in Jordan. *Palestine Explor. Quart.* **98**, 8–72.
- Kuijt, I. & Goring-Morris, A. N. 2002 Foraging, farming and social complexity in the Pre-Pottery Neolithic of the South-Central Levant: a review and synthesis. *J. World Prehist.* **16**, 361–440. (doi:10.1023/A:1022973114090)
- Kuijt, I., Finlayson, B. & Mackay, J. 2007 Pottery Neolithic landscape modification at Dhra'. *Antiquity* **81**, 106–118.
- Lovell, J. L., Richter, T., McLaren, P. B., McRae, I. K. & Abu Shmeis, A. I. 2005 The first preliminary report of the Wadi Rayyan Archaeological Project: the survey of el Khawarij. *Annu. Dept Antiq. Jordan* **49**, 189–200.
- Lovell, J. L., Thomas, D. C., Miller, H., Wesselingh, K., Kurzwaska, A., McRae, I. K., Elias, C., Obeidat, E. & Abu Shmeis, A. (with a contribution by L. Weeks). 2007 The third preliminary report of the Wadi Rayyan Archaeological Project: the second season of excavations at el-Khawarij. *Annu. Dept Antiq. Jordan* **51**, 103–140.
- Mabry, J. M., Donaldson, L., Gruspier, K., Mullen, G., Palumbo, G., Rawlings, N. M. & Woodburn, M. A. 1996 Early town development and water management in the Jordan Valley: investigations at Tell el-Handaquq North. *Annu. Am. Schools Orient. Res.* **53**, 115–154.
- Maher, L. In press. People and their places at the end of the Pleistocene: evaluating perspectives on physical and cultural landscape change. In *Hunters in transition* (eds B. Finlayson & G. Warren). Levant Supplementary Series. Oxford, UK: Oxbow and CBRL.
- Mithen, S. J. 2003 *After the ice: a global human history, 20 000–5000 BC*. London, UK: Weidenfeld & Nicolson.
- Mithen, S. J. & Black, E. (eds) In press. *Water, life and civilisation: climate, environment and society in the Jordan Valley*. Cambridge, UK: Cambridge University Press.
- Mithen, S. J., Jenkins, E., Jamjoum, K., Nuimat, S., Nortcliff, S. & Finlayson, B. F. 2008 Experimental crop growing in Jordan to develop methodology for the identification of ancient crop irrigation. *World Archaeol.* **40**, 6–25. (doi:10.1080/00438240701843561)

- Nadel, D. & Hershkovitz, I. 1991 New subsistence data and human remains from the earliest Levantine epipalaeolithic. *Curr. Anthropol.* **32**, 631–635. (doi:10.1086/204012)
- Nadel, D. & Werker, E. 1999 The oldest ever brush hut plant remains from Ohalo II, Jordan Valley, Israel (19 000 BP). *Antiquity* **73**, 755–764.
- Nadel, D., Carmi, I. & Segal, D. 1995 Radiocarbon dating of Ohalo II: archaeological and methodological implications. *J. Archaeol. Sci.* **22**, 811–822. (doi:10.1016/0305-4403(95)90010-1)
- Najjar, M., Aub Dayyeh, A. S., Suleiman, E., Weisgerber, G. & Hauptmann, A. 1990 Tell Wadi Feinan: the first Pottery Neolithic Tell in the South of Jordan. *Annu. Dept Antiq. Jordan* **34**, 27–56.
- Noy, T. 1989 Gilgal: a Pre-Pottery Neolithic site. *Paléorient* **15**, 11–18.
- Oleson, J. 2007 Nabatean water supply, irrigation and agriculture: an overview. In *The world of the Nabateans* (ed. K. D. Politis), pp. 217–249. Stuttgart, Germany: Franz Steiner Verlag.
- Ortloff, C. R. 2005 The water supply and distribution system of the Nabatean city of Petra (Jordan), 300 BC–AD 300. *Camb. Archaeol. J.* **15**, 93–109. (doi:10.1017/S0959774305000053)
- Peltenberg, E., Colledge, S., Croft, P., Jackson, A., McCartney, C. & Murray, M. A. 2000 Agropastoralist colonization of Cyprus in the 10th millennium BP: initial assessments. *Antiquity* **74**, 844–853.
- Philip, G. 2008 The Early Bronze Age I–III. In *Jordan: a reader* (ed. R. Adams), pp. 161–226. London, UK: Equinox.
- Por, D. F. 2004 The Levantine waterway, riparian archaeology, paleolimnology, and conservation. In *Human paleoecology in the Levantine corridor* (eds I. Goren-Inbar & J. Speth), pp. 5–20. Oxford, UK: Oxbow Books.
- Rambeau, C., Finlayson, B., Smith, S., Black, S., Inglis, R. & Robinson, S. In press. Palaeoenvironmental reconstruction at Beidha, southern Jordan (*ca* 18 000–8500 BP): implications for human occupation during the Natufian and Pre-Pottery Neolithic. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Robinson, S. A., Black, S., Sellwood, B. W. & Valdes, P. J. 2006 A review of palaeoclimates and palaeoenvironments in the Levant and Eastern Mediterranean from 25 000 to 5000 years BP: setting the environmental background for the evolution of human civilisation. *Quatern. Sci. Rev.* **25**, 1517–1541. (doi:10.1016/j.quascirev.2006.02.006)
- Rollefson, G. O. 1989 The aceramic Neolithic of the southern Levant: the view from ‘Ain Ghazal. *Paléorient* **9**, 29–38. (doi:10.3406/paleo.1983.4339)
- Rollefson, G. O. & Köhler-Rollefson, I. 1989 The collapse of early Neolithic settlements in the southern Levant. In *People and culture change: Proc. 2nd Symp. Upper Palaeolithic, Mesolithic and Neolithic Populations of Europe and Mediterranean Basin* (ed. I. Hershkovitz), pp. 59–72. BAR International Series 508. Oxford, UK: Archaeopress.
- Sanders, W. T., Parsons, J. R. & Santley, R. S. 1979 *The Basin of Mexico: ecological processes in the evolution of a civilisation*. New York, NY: Academic Press.
- Scarborough, V. L. 2003 *The flow of power: ancient water systems and landscape*. Sante Fe, NM: School of American Research.
- Sharp, R. 2008 A poisoned paradise: Cambodia’s water crisis. *The Independent*, 28 March 2008.
- Simmons, A. & Najjar, M. 1996 Current investigations at Ghwair I, a Neolithic settlement in southern Jordan. *Neolithics* **2**, 6–7.
- Simmons, A., Rollefson, G. O., Kafafi, Z. & Moyer, K. 1989 Test excavations at Wadi Shu‘eib, a major Neolithic settlement in Central Jordan. *Annu. Dept Antiq. Jordan* **33**, 27–42.
- Smith, M. 2005 City-size in late classic Mesoamerica. *J. Urban Hist.* **31**, 403–434. (doi:10.1177/0096144204274396)
- Smith, S., Wade, A., Black, E., Brayshaw, D. & Rambeau, C. In press. From global climate change to local impact in Wadi Faynan, southern Jordan: ten millennia of human settlement in its hydrological context. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Stekelis, M. 1966 *Archaeological excavations at ‘Ubeidiya 1960–1963*. Jerusalem: Israel Academy of Sciences and Humanities.

- Steward, J. H. (ed.) 1955 *Irrigation civilization: a comparative study*. Washington, DC: Pan American Union.
- UNEP. 2007 *GE04 Global environment outlook (environment for development)*. New York, NY: United Nations Environment Programme.
- UN Water. 2007 Coping with water scarcity: challenges of the twenty-first century. Prepared for World Water Day, 2007. See <http://www.unwater.org/wwd07/download/documents/escarcity.pdf>.
- Valla, F. R., Khalaily, H., Samuelian, N., Boucquentin, F., Delage, C., Valentin, B., Plisson, H., Rabinovich, R. & Belfer-Cohen, A. 1999 Le Natufian final and les nouvelles fouilles à Mallaha (Eynan), Israel 1966–1977. *J. Israel Prehist. Soc.* **28**, 105–176.
- Wade, A., Holmes, P., el-Bastawesy, M., Smith, S., Black, E. & Mithen, S. J. In press. The hydrology of Wadi Faynan. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Whitehead, P. G., Smith, S. J., Wade, A. J., Mithen, S. J., Finlayson, B. L. & Sellwood, B. 2008 Modelling of hydrology and potential population levels at Bronze Age Jawa, Northern Jordan: a Monte Carlo approach to cope with uncertainty. *J. Archaeol. Sci.* **35**, 517–529. (doi:10.1016/j.jas.2007.05.001)
- Whitehead, P. G., Smith, S. & Wade, A. In press. Modelling water resources and climate change at the Bronze Age site of Jawa in northern Jordan: a new approach utilising stochastic simulation techniques. In *Water, life and civilisation: climate, environment and society in the Jordan Valley* (eds S. J. Mithen & E. Black). Cambridge, UK: Cambridge University Press.
- Winpenny, J. T. 2000 Managing water scarcity for water security. See http://www.wca-infonet.org/servlet/BinaryDownloaderServlet?filename=documents/1354.Managing_water_scarcity_for_water_security.2001-11-13.pdf&refID=1354.
- Wittfogel, K. A. 1957 *Oriental despotism: a comparative study of total power*. New Haven, CT: Yale University Press.