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REPORT

The history and fate of the Nubian Sandstone Aquifer springs in the oasis depressions of the Western Desert, Egypt

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Abstract Extraction of groundwater for agriculture has resulted in the loss of springs across arid regions of the globe. The history and fate are recorded of the artesian springs of Egypt's Western Desert, from ancient times to the present, spanning the rise and fall of the great civilisations from the Pharoanic dynasties to Persian, Greek and Roman conquests. The study area includes oases Kharga, Dakhla, Bahriya, Farafra and Siwa, and several outer and small oases around Siwa and the edge of the Qattara Depression. The region is hyper-arid, receiving 10 mm or less average annual precipitation and evaporation rates are in the vicinity of 3,000 mm/a. Groundwater in the oases is largely derived from bores discharging from the Nubian Sandstone Aquifer. Based on an extensive survey, conducted for the first time, attention is drawn to the rapid demise of springs as a result of modern irrigation schemes which continue to deplete groundwater supplies.

Keywords Egypt · Groundwater development · Arid regions · History of hydrogeology · Oasis

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Introduction

An 'oasis' is an island of verdant fertility sustained by groundwater in a barren and desolate landscape and has its origin from *ouahe* in the demotic language of ancient Egypt. The word intimates the cultural and biological significance of groundwater discharging to the surface and this has been recently realised through efforts to determine the cultural and biological values of ancient wells and water sources (Beaumont 1971; Lightfoot 1996; Hercus and Clarke 1986) as well as naturally occurring springs (Fensham and Fairfax 2003; Harris 1981; Ashley et al. 2002; Harvey et al. 2007; Shepard 1993; Stevens and Meretsky 2008; Powell et al. 2015).

Over the last century, increasing demand for groundwater supplies has had considerable impact on aquifers around the globe of which the earliest, and often most visible sign of diminished pressure, is the loss of springs and collapse of traditional irrigation systems with the biological and human communities they support. Their cultural and natural values become amplified when they are sources of permanent water in arid environments (Fensham et al. 2011; Powell et al. 2015; Aldumairy 2005), and perhaps the most iconic representation are the oases in the Sahara Desert which forms one of the most inhospitable environments on Earth. The oases of northern Africa have an ancient human history, but they are currently in the process of rapid transformation.

In Egypt's western deserts, irrigation schemes that receive their water from modern bores have brought new areas under cultivation raising a variety of environmental concerns. Artificial extraction through bores has resulted in piezometric declines and the requirement to pump groundwater from deeper and deeper sources (Lamoreaux et al. 1985). The artesian supplies beneath the Western Desert are partially comprised of non-renewable fossil water derived from pluvial

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phases throughout the Pleistocene (Dabous and Osmond 2001; Manfred and Brinkman 1989), and while some assessments have indicated that the volume of groundwater is sufficient to support future development (Nour 1996), others studies emphasise that under proposed extraction rates groundwater will become unavailable, possibly within the next century (Dabous and Osmond 2001; Ebraheem et al. 2002; Voss and Soliman 2014). Salinisation and waterlogging is reducing the productivity of agricultural land around oases where extraction through artificial bores is excessive (Masoud and Koike 2006; Misak et al. 1997).

Prior to the advent of modern drilling activity, agriculture and communication across vast distances of the Western Desert was entirely dependent on ancient artesian wells, known as 'Romanic' springs as well as naturally occurring groundwater vents. Mirroring patterns across the Middle East (Lightfoot 1996), economic focus has rapidly shifted away from these antiquated features of the landscape in favour of bores and diesel-operated pumping stations. There has been intermittent mention of the decline and expiration of ancient wells in western Egypt (Idris 1996) and a loss of 'Romanic' springs is highlighted in an analysis concerning the long-term sustainability of groundwater extraction (Lamoreaux et al. 1985). Based on an extensive field survey of over 600 sites, the first comprehensive analysis is presented of the consequences of groundwater extraction on the iconic springs and ancient artesian wells of the Western Desert. This report provides an overview of the cultural history of the oases, describes features of the wells and springs, and collates details of their status, current uses and decline.

Study area and oasis hydrogeology

The current study area comprises the oases of the Western Desert including Kharga, Dakhla, Bahriya, Farafra and Siwa as well as several outer and small oases around Siwa and the edge of the Qattara Depression (Fig. 1). Due to logistical constraints, the Qattara Depression was excluded from the analysis. The region is hyper-arid, receiving 10 mm or less average annual precipitation and evaporation rates are in the vicinity of 3,000 mm/a (Shahin 2007). Groundwater in the oases is largely derived from bores discharging from the Nubian Sandstone Aquifer (NSA). This aquifer is comprised of a wedge-shaped sandstone deposit spanning early Paleozoic to Cretaceous age with the thin edge of the wedge outcropping to the south in the highlands of Sudan and Chad. Within Libya and Egypt the aquifer is 1–2 km deep and confined beneath impermeable upper Cretaceous-Eocene beds (Dabous and Osmond 2001; Shata 1982). Salinity increases south to north and the basin can be divided into three broad hydro-chemical zones (Himida 1970): (1) a region of freshwater extending from the southern edge of the basin to Bahriya (~500 ppm), (2) a region of brackish water north of Bahriya and extending from Siwa to the Qattara Depression (~1,000 ppm), (3) a region of highly saline waters extending along the Mediterranean coast (≥100, 000 ppm). Springs and ancient artesian wells tend to occur along fault lines as well as in the lowest parts of the oases where palaeo-drainage has eroded the confining layers above the sandstone aquifer (Fig. 1). The most northerly depressions extend below sea level with the Qattara Depression reaching 135 m below sea level.

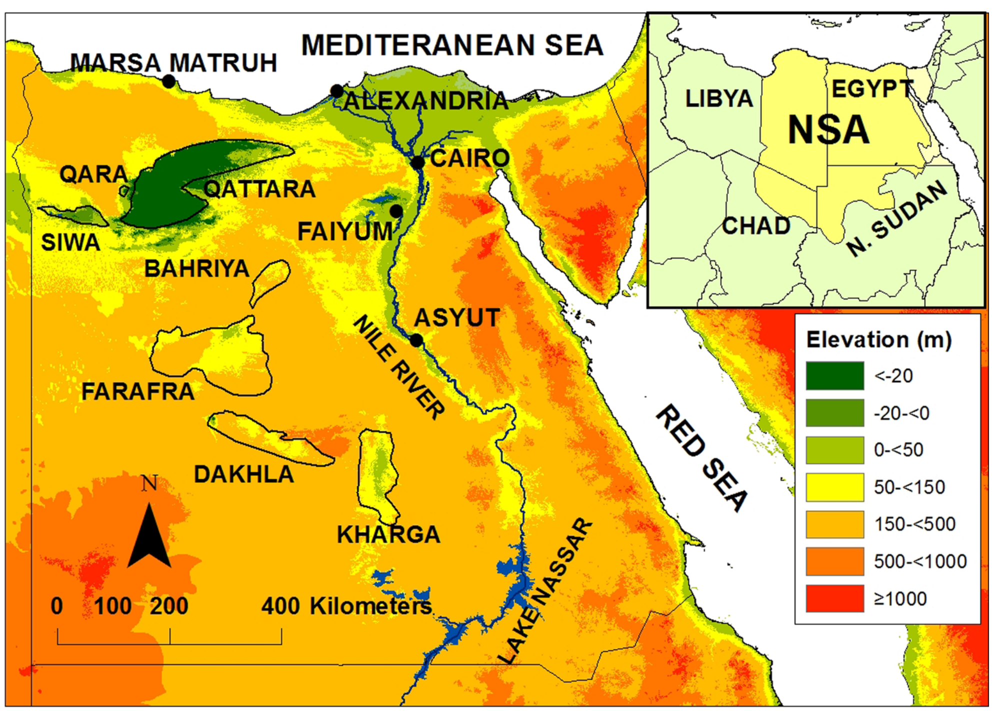

Fig. 1 Major oases and depressions of the Western Desert in Egypt. Major cities and settlements mentioned in the text are indicated by *black dots*. Shades of *green* represent areas of low elevation which extend to 135 m below sea level (mbsl) in the Qattara Depression. The extent of the Nubian Sandstone Aquifer (*NSA*) is indicated on the inset map in *yellow*

Groundwater sources within the NSA are poorly resolved but it is recognised that current recharge is negligible with mean annual rainfall in the Tibesti, Ennedi and Malhu Highlands less than 190 mm. Recharge is thought to have primarily occurred during pluvial phases throughout the Quaternary with recent events having a periodicity of several thousand years. The most recent period of substantial recharge occurred 8,000–6,000 BP when the unconfined sediments forming the recharge areas of the NSA were receiving 300–450 mm annual rainfall (Kuper and Kröpelin 2006; Kröpelin et al. 2008) Since the most recent pluvial phase, natural discharge from the NSA has probably been in decline (Ebraheem et al. 2002; Manfred and Brinkman 1989); however, the rates of declining pressure due to climatic fluctuations has been vastly exceeded in the regions where cones of diminished aquifer pressure has formed beneath clusters of bores. Extraction and natural discharge greatly exceeds natural aquifer intake and the NSA is currently being depleted (Manfred and Brinkman 1989; Dabous and Osmond 2001).

History of the oases and their use

The spring fed oases of western Egypt have supported settlement, migration and trade for millennia and have a rich cultural history dating back to the Pleistocene. Over this period, fluctuations between arid and pluvial phases have been associated with patterns of human and hominid occupation (Abouelmagd et al. 2012; Smith et al. 2004a). The Western Desert was predominately arid in the late Pleistocene (Nicoll 2001) and sites displaying evidence of hunter-gathering, agriculture and cattle husbandry, have been associated with a pluvial phase from the onset of the Holocene which continued to about 4,600 BP (Mandel and Simmons 2001; Kröpelin et al. 2008). Wadis were subject to enhanced erosion and tablelands would have supported savanna vegetation; however, this wet phase was probably less extreme than earlier Pleistocene events (Smith et al. 2004b). As the climate became increasingly arid in the late Holocene, a general exodus from the desert occurred (Bubenzer and Riemer 2007) and habitation would have been confined to the depression floor and areas around permanent artesian springs (Fig. 1; Briois et al. 2012).

Several monuments and ancient texts provide compelling evidence that oases of Bahriya, Farafra, Dakhla and Kharga were brought under centralised control by the kingdoms of the Nile Delta before the end of the 6th Dynasty (2191 Before Common Era (BCE); Fakhry 1974). Current hyper-arid conditions prevailed across the Western Desert and the oases and lines of springs were of immense economic and strategic importance. They formed the western flank of defence from Libya as well as the basis of extensive, and lucrative, caravan routes (Fakhry 1974; Fakhry 1973).

The springs of Kharga Oasis are generally associated with a north–south orientated fault line (Idris 1996) which, historically, supported the 'Darb Arbeen', or 'Forty days' caravan route extending from the upper Nile, through Kharga to Asyut. Several routes extended east to the Nile and west towards the outer oases of Dakhla and Farafra. Siwa Oasis was located at the junction of several major North African caravan routes. To the north and north west, numerous routes extended to the Mediterranean coast as well as the Libyan interior. To the south east, Siwa was connected to Bahriya by a series of small outer oases, while to the north east, a camel trail, Masrab Khalda, extended to the coast via Qara Oasis and along the north-western face of the Qattara Depression. A telegraph line linking Siwa to the coast was later established along this route (see Mather 1944).

Pre-industrial societies often display deep cultural and spiritual affiliations with water. The oases became centres of worship and prophecy; however, their status within ancient belief systems also reflects their secular significance for the various dynasties and empires that ruled Egypt. After the defeat of the Egyptian pharaoh Psamtik II at the Battle of Pelusium (525 BCE), Egypt became a province of the Persian Empire under the reign of Cambyses II. Located in the heart of Kharga Oasis, Hibis Temple was completed under the reign of the Persian monarch Darius I and dedicated to Amun-ra, the pre-eminent deity of ancient Egypt (Beadnell 1909).

In Siwa Oasis, the oracle temple of Amun-Ra has been immortalised through its association with Alexander the Great. Located upon a small residual Miocene hill in the heart of the depression, the ruins are set among numerous springs (Fig. 2). After defeating the Persian Empire and acquiring the territories of Egypt, the Macedonian King travelled to Siwa in the early part of 331 BCE to consult the oracle. Amun-Ra was considered synonymous with Zeus, the supreme deity of the

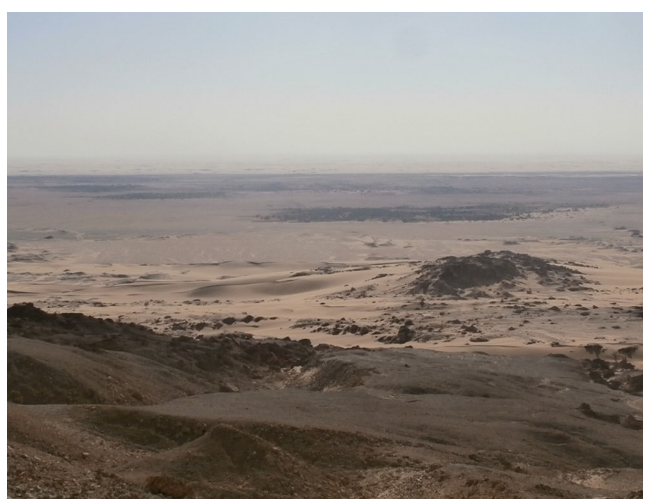

Fig. 2 Kharga Oasis showing deeply eroded gullies along the eastern edge of the depression. Cultivated areas in the distance, represented by *dark patches*, were formerly fed by artesian springs but now rely on bores

Greek pantheon, and many Greek scholars considered Egypt to be the centre of philosophy, culture and art and mysticism (Fakhry 1973). Alexander had been tutored by Aristotle in his youth and was steeped in classical Greek culture. In addition to the rumours of his own divine birth, Alexander claimed to be a descendant of Achilles and wished to follow in the footsteps of Perseus and Hercules who had also consulted the oracle at Siwa and were the offspring of Zeus (Freeman 2011).

The historical account of Alexander's journey to Siwa is steeped in mythology and the accuracy of the details cannot be verified. It is said that the party left from Marsa Matruh and followed the 'Masrab al-Istabl' caravan route which, according to historical maps, may have been supplied by only a few temporary cisterns or wells. At first the party ran out of water until a miraculous storm allowed them to replenish their supplies. Later, they became lost after a fierce sand storm but were guided to the oasis by two ravens, or two serpents. The questions that Alexander personally posed to the oracle are a matter of debate (Fakhry 1974; Aldumairy 2005; Belgrave 1923); however, he emerged from Siwa as not only as king of Egypt, but the son of Amun-Ra and conqueror of the world.

Alexander the Great's death in Babylon in 323 BCE led to the break-up of his empire and the establishment of the Ptolemaic dynasty in Egypt which lasted three centuries until Egypt was annexed by the Roman Empire in 30 CE (Common Era). The fame of the oracle temple declined and by the third century, Christianity had spread throughout Egypt; however, Siwa's isolation meant that people possibly continued worshiping Egyptian gods until the Arabian conquest of North Africa, converting to Islam sometime after 642 CE.

Siwa's remoteness contributed to the development of a unique culture and traditions including open tolerance of homosexuality which persisted until modern times (Fakhry 1973), as well as rich folk lore in relation to the springs. One custom included the ritual bathing of women in Tamusi spring (Fig. 3), either before a wedding or after she was widowed. In the latter case, the unfortunate woman was thought to have come under a powerful 'evil eye' and was ostracised for 40 days before returning to the spring to bathe and re-enter society. The people of Siwa are descendants of Berber tribes and speak a distinct dialect unrelated to Arabic, which is otherwise spoken throughout the other oases. Historical settlement of Bedouin around parts of the oasis has resulted in some springs having Arabic names, but the majority remain uniquely Siwan.

Fig. 3 Ruins of the Oracle Temple of Amun-Ra in Siwa Oasis. This site has been immortalised through its association with Alexander the Great

Throughout the oases, the reference to ancient wells and water sources as 'Romanic' springs ('Ain Romani' in Arabic) relates to Egypt's occupation by the Roman Empire. While the antiquity of improvements ranges from pre-Romanic, Islamic to late pre-industrial times (Lamoreaux et al. 1985), the term encapsulates the Roman Empire's legacy in establishing irrigation schemes and watering stations across Egypt (see Murphey 1951; Meredith 1952). Examples of 'Romanic' springs include shallow wells lined with timber or masonry (Aldumairy 2005), ancient boreholes dug by rudimentary percussion drills and lined with timber casing (Lamoreaux et al. 1985; Beadnell 1909) as well as qanats, a system which delivers groundwater to the surface along lateral, sloping tunnels from a shallow water-bearing layer or water source (Beaumont 1971; Lightfoot 1996; Cressey 1958; Lightfoot 2000).

Many ancient wells and irrigation systems were probably established on top of naturally occurring springs or water sources and, depending on the local aquifer and elevation, could yield artesian or sub-artesian supplies. Springs required periodic cleaning (Fig. 3) while mound formation (see Roberts and Mitchell 1987) around small spring vents or artificial boreholes could cause the water supply to become sub-artesian, necessitating additional works such as excavating and lowering the mound or establishing qanats. Mound formation, lack of cleaning and sand encroachment almost certainly led to springs being periodically abandoned and potentially re-occupied and rehabilitated centuries later.

Irrigation methods based around the exploitation of springs would have continued largely unaltered until the introduction of modern percussion drills in the mid-19th century, which revolutionised agriculture throughout the oases. In Dakhla Oasis, all of the bores were initially drilled by just one rig though many of the shafts were still lined with timber from the Sunt tree (*Acacia nilotica*; Fig. 4; King 1917). In Kharga Oasis in the early 20th century, modern drilling operations (Fig. 5) had obtained depths of 122 m below the confining grey shales of the upper Cretaceous (~300 m from the surface), though later obtained depths up to 750 m below the surface (Lamoreaux et al. 1985). After the 1950s, the Egyptian government initiated an extensive programme of agrarian reform and land reclamation in the Western Desert, purportedly inspired by historical accounts of the oases thriving in ancient times (Voll 1980; Murphey 1951). Ambitious drilling schemes and the establishment of pumping facilities has continued until the present as well as in neighbouring countries seeking to exploit the finite resources of the NSA.

Fig. 4 Springs required periodic cleaning. This image shows local people cleaning Tamusi spring in Siwa (source Belgrave 1923)

Sources and artesian spring survey

Surveying the oases commenced with a compilation of historical sources (Table 1) and progressed through the engagement of local knowledge. The survey focussed entirely on sites depicted or known locally as 'Ain', the Arabic for spring and, henceforth, 'spring' will be used to refer to both ancient artesian wells and natural springs throughout this report. In most cases, oasis inhabitants could locate the springs as well as many others not located on the maps; however, where information was absent, or the location of inactive springs forgotten, relevant maps were geo-referenced in a geographical information system (GIS) to provide approximate coordinates to facilitate a more localised search. The scale and completeness of cartographic sources (Table 1) varied between oases. It is likely that the oases were not equally represented during the survey.

WOODEN PIPES FOR ARTESIAN WELLS, DAKHLA OASIS: SUNT TREE ON RIGHT

Fig. 5 Timber casing used for early boreholes at Dakhla Oasis (source: King 1917)

Kharga Oasis

Out of 255 identified springs, only three remain active. Ain Lebekha yields a sub-artesian supply from a series of qanats, while Ain Amour and Dafnis Sharq are located on the edge of the depression and are not associated with the Nubian aquifer.

Table 1 Map sources for Western Desert oases. Details for individual oases are given in Table S1 of the electronic supplementary material (ESM)

Oasis	Map source
Bahriya	Baheriya Oasis from the Surveys of Ball and Beadnell, 1:100,000, Survey of Egypt (1916); Baharia and Farafra Oases and their Approaches, 1:500,000, Survey of Egypt, (1916); Baharia, 1:500,000, Survey of Egypt (1935); Baheriya Oasis, 1:100,000, Dept. of Survey and Mines (1939); Fakhry (1974)
Dakhla	Dakhla Oasis Sheet 4, 1:500,000, Survey Dept. (1900); Kharga and Dakhla Oases and their Approaches, 1:500,000, Survey of Egypt (1916); Qena No. 8, 1:500,000, Survey of Egypt (1946)
Farafra	Baharia and Farafra Oases and their Approaches, 1:500,000, Survey of Egypt (1916); Baheriya, 1:500,000, Survey of Egypt (1935); Fakhry (1974)
Kharga	Kharga Oasis Sheet D4, 1:500,000, Survey of Egypt (1916); Karga Oasis, Sheets 1–13, 1:50,000, Survey Dept. (1907); Qena No. 8, 1:500,000, Survey of Egypt (1946)
Siwa	Siwa, 1:100,000, Dept. Survey and Mines (1939); El Qaneitra, 1:100,000, Dept. of Survey and Mines (1939)
Outer oases	Qara, 1:100,000, Dept. of Survey and Mines (1940); Tibaghbah, 1:100,000, Dept. of Survey and Mines (1940); El-Bahrein, 1:100,000, Dept. of Survey and Mines (1941); Geological Map of Egypt NH 35 SW Siwa, 1:500,000 (1986)

Fig. 6 Flowing artesian bore in Kharga Oasis (source: Beadnell 1909)

Ain Lebakha supported a caravan route to Dakhla Oasis which ran past another qanat fed spring, Ain Um Abidabib, as well as Ain Amour, and is perhaps one of the best preserved examples of a functioning qanat system in the Western Desert (Fig. 6). Located at the base of a shallow water-bearing sandstone outcrop, extensive tunnels collect increasing amounts of water by intercepting fissures in the rock. Probably constructed during the Roman period (Schacht 2003), the site contains the ruins of a fortress outpost (Fig. 7) and several tombs. The qanats were formerly filled with windblown sand; however, after being cleared in recent decades, the spring maintains a small pond at the end of two tunnels, while the third remains buried. The area now supports a small farm, though water is supplemented by a deep bore.

Ain Um Abidabib, roughly 12 km to the west, shares a similar geological setting as Ain Lebekha and supported an extensive fortress outpost. The spring is no longer active as the tunnels have either collapsed or filled with sand. Beadnell (1909) observed that after a long period of abandonment, the site was re-occupied at the turn of the 20th century and clearing the tunnels yielded a modest supply. The spring consisted of at least four main qanats with a combined total length of over 14 km (Fig. 8).

Ain Amour (Fig. 9) and Dafnis Sharq (east Dafnis) occur on high escarpments and are rare examples of gravity-fed springs and perched aquifers derived from local, albeit limited, rainfall. Both springs share a similar geological setting at the base a limestone plateau. The ruins of a fortress and temple can be found at Ain Amour which stands over 300 m from the depression floor and a slightly brackish supply can be obtained from a hole surrounded by dense stands of *Juncus ridgidus*. Recent archaeological investigations at the site revealed the presence of a *serekh*, or royal inscription, amongst some rock graffiti (Ikram and Rossi 2004), suggesting that the trail between the spring and Dakhla Oasis was being used during the early Dynastic period. Dafnis Sharq has been covered by

Fig. 7 Entrance to one of the qanats of Ain Lebekha

Fig. 8 Fortress outpost at Ain Lebekha

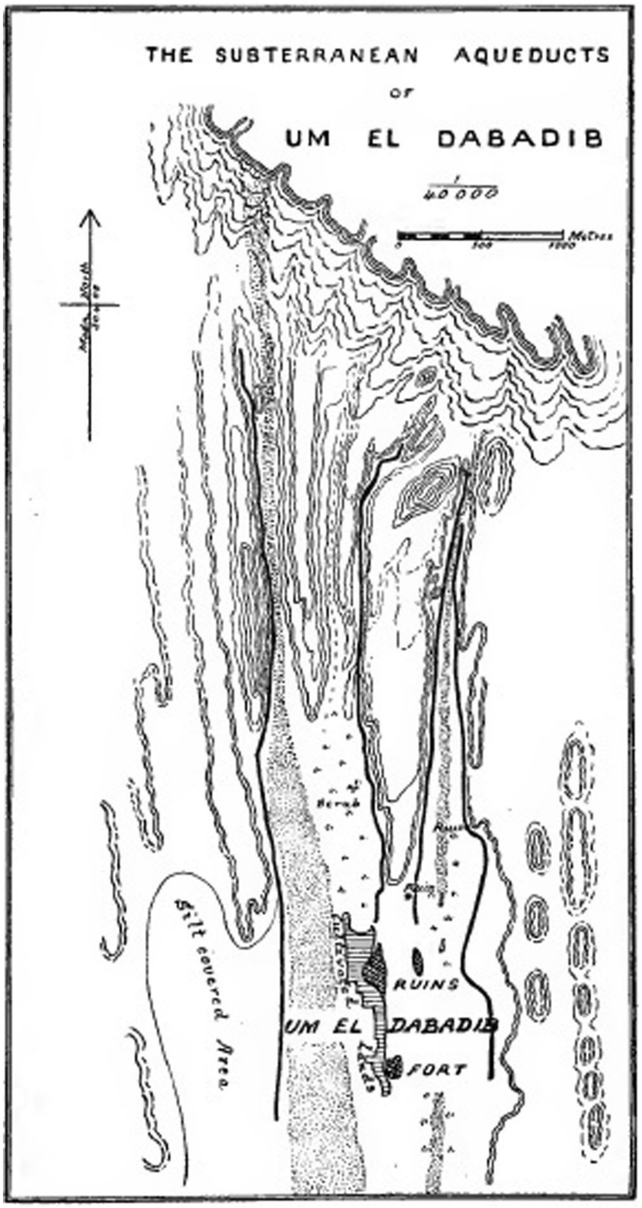

Fig. 9 Extensive rock aqueduct system of Um Abidabib which supported a cultivated area and Roman fort (Beadnell 1909)

sediments but the presence of groundwater is clearly indicated by patches of vegetation including a dense stand of reed (*Phragmites australis*). The 1:50,000 historical map series of Kharga (Table 1) indicate the presence of Coptic inscriptions on the rocks near the spring; however, these were not identified during this survey.

Dakhla

Out of 48 identified springs in Dakhla Oasis, only one remains active. Situated in the middle of a hotel complex, Ain Baiyad (Fig. 10) discharges from a shallow, concrete lined excavation. Throughout the oasis, many inactive springs have been

Fig. 10 Ain Amur emerges along a high escarpment and supports a dense stand of *Juncus ridgidus*

destroyed or been replaced by pumped bores. Located in the centre of an ancient abandoned township, Ain Allam and Ain Baheriya were non-flowing wells but both have been filled in. Ain Rakhla was smothered by an encroaching dune and a bore has been placed within 20 m in its vicinity. Bores and pumping stations now mark the position of Ain Magnuun, Mansur, Nageem, Dirman and Sheghala.

Farafra Oasis

Of the 28 identified springs at Farafra Oasis, four remain active. Ain Sewr (Fig. 11), Khadra and Maqi are located within a radius of 14 km of each other in the northern extremity of the oasis and would have been critical stepping stones along the caravan route from Baheriya to Qasr Farafra, the main settlement of the oasis. Ain Dalla is situated in the north-western part of the oasis, and supported a

Fig. 11 Ain Baiyad is the last flowing spring of Dakhla Oasis

caravan trail leading to Siwa as well as a second route into the interior of Libya. In the 1920s, works were undertaken to clear and line the spring with concrete, purportedly to assist Libyan refugees who were pushed out of their homes by Italian colonists (Fakhry 1974). Ain Sewr and Khadra yield modest supplies between 6 and 8 L/min and, like Ain Maqfi and Dalla, maintain vegetated mounds rising several metres above the plain. Large mound springs with associated qanats are a feature of several inactive springs in Farafra including Ain Bishoi, Goshna, Kiffrien, Badash and Gello.

Bahriya

At Bahriya Oasis, only two of the 69 identified springs remain active. Ain Fezeya and a second unnamed spring 230 m away, produce a small trickle at the base of a rock outcrop, though it is also possible that some of this is run-on water from other sources. Together with Ain Bishmu, the springs are located at the base on an escarpment associated with the Bawati fault (Idris 1996). Historical depictions of Ain Bishmu (Fig. 12) suggest it produced a considerable flow and, according to one description from the late 1930s, joined the waters of Ain Dardir and ran in a stream for about 15 m before dropping into a cataract and irrigating fields below (Fakhry 1974). Currently Ain Bishmu consists of a dry, rubbish-filled ditch. Like many springs in the oasis, when flows from Ain Bishmu diminished, it was 'rehabilitated' (Fig. 13) by placing two bores in the vicinity (Idris 1996).

Throughout the oasis, there were several examples where remote springs along the ancient caravan trails had disappeared, presumably after being abandoned and later covered with migrating sand. According to historical sources (Table 1), Ain Mallaqa was located along the north-western edge of the depression on the caravan route to Fayoum and the Nile; however, this area now consists of a monotonous patch of desert and there is no evidence of the spring. Ain Khomen was located on the southern extremity of Bahriya along the route to Farafra. A map of Bahriya published in 1916, described this spring as being mostly 'sanded up' and that the water was 'not to be depended upon'. The spring is now almost certainly covered over and there appears to be no local knowledge of this spring.

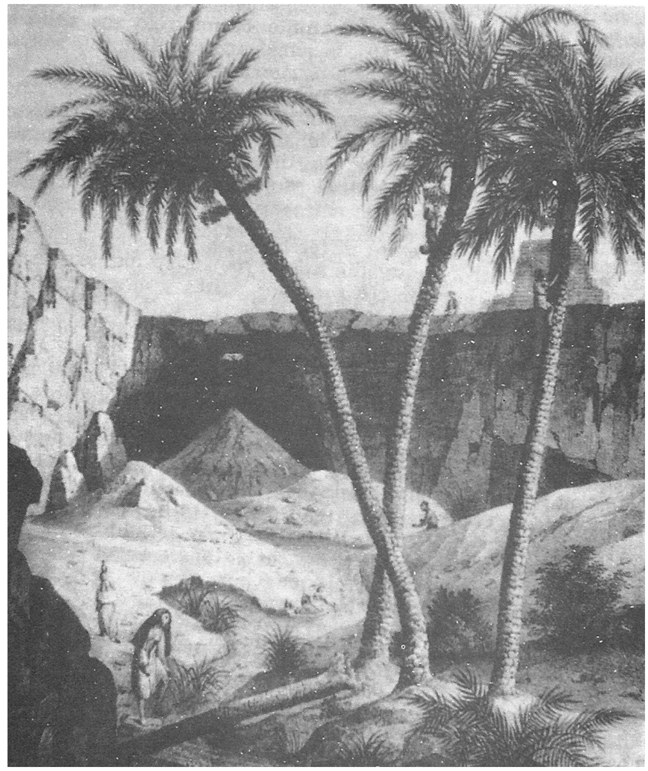

Fig. 13 Historical depiction of Ain Bishmu showing flowing stream and date palms ca. 1820 (source: reproduced in Fakhry 1974)

Fig. 12 Ain Sewr is a flowing spring maintaining a large vegetated mound

Siwa

At Siwa Oasis, out of 190 identified springs, 159 remain active, most of which are still used for irrigation. Several inactive springs have water levels only a few metres from the surface and maintain utility by pumping. In recent decades, the Egyptian government as well as private investors have sponsored numerous works excavating and sealing springs with concrete as well as establishing networks of concrete irrigation channels (Fig. 14). The deepest spring encountered during the survey was Ain Zaytuun at approximately 11 m and, only four unenclosed springs can be found in the cultivated areas of Siwa. While some of the ancient works are likely to have been damaged or destroyed, evidence of the original construction method can be found at the lower levels of Ain Abu Shruf (Aldumairy 2005).

Fig. 14 One of the bores occupying the site of Ain Bishmu

Outer oases

With the exception of Qara Oasis (Fig. 15), the outer oases (Table 2) around Siwa and the edge of the Qattara depression are uninhabited, though the presence of numerous artefacts as well as major archaeological remains such as temples and rock tombs, indicates that they were occupied in ancient times (Cosson 1937; Fakhry 1973). The springs of Qara are similar to Siwa as they have been generally excavated and lined with concrete. The outer oases are characterised by numerous sabkha formations and permanent salt lakes. Temiera Depression supports several lakes at approximately knee-depth and sufficiently shallow to wade across. Closer inspection revealed deep subaqueous spring vents extending several metres below the lake floor. Tibaghbah Depression contains another unusual spring formation comprised of an Eocene limestone outcrop with small 1–5 cm stalactites dripping with salt water (Fig. 16). This spring type is locally referred to as 'Qattara' or 'dripping' spring. Springs sharing the same flow characteristic and name can also be found along a small cliff face in Qara Oasis as well as the northwestern face of the Qattara Depression from which the entire depression takes its name.

Fig. 15 Tamusi Spring in Siwa Oasis

Discussion

The results of this survey are consistent with studies conducted in other arid settings where land-use intensification and ambitious groundwater investment schemes have led to the dramatic, sudden and sometimes 'cataclysmic' extinction of artesian springs and ancient irrigation systems (Fairfax and Fensham 2002; Powell et al. 2015; Closas 2014). With a few exceptions, the springs of Kharga, Dakhla, Farafra and Bahriya have been obliterated.

Many springs ceased flowing after the 1950s as a result of desert reclamation schemes. In Kharga Oasis, the water level was reported to have dropped 17 m between 1965 and 1979, and by 1975, all of the modern bores (Fig. 5) had stopped flowing (Lamoreaux et al. 1985). In Dakhla Oasis, the remains of animal-driven water wheels, or *sakias*, were observed around several springs which were probably installed after water levels dropped in the ancient wells before being completely discarded. Abandoned fields and dead trees (Fig. 17) as well as historical references and descriptions, further highlight the recent utility of springs which are now inactive. In Kharga Oasis, Ain Estakherab (Fig. 18) was the 'finest well in the Libyan Desert' (Beadnell 1909) and flowed into a channel that was also fed by Ain Margrin. As depicted on the 1:50,000 map series published in 1907 (Table 1), an irrigation canal from these springs stretched for over 10 km. The 1:500,000 'Bahariya', 'Matruh' and 'Qena' maps series published between 1941 and 1946 (Table 1), include annotated descriptions of the springs. In Kharga Oasis, Ain Foq el-Dom watered 60 feddans (25 ha), while Ain Dakhahin

Table 2 Outer and abandoned oases around Siwa and the edge of the Qattara Depression

Oasis	Distance from Siwa (km)	Bearing	Caravan route	Oasis description
Shiyata	40	289°	Siwa-Jaghboob	Salt lake surrounded by date palms and dense reed
Girbe	25	310°	Siwa-Jaghboob	Vegetated depression including several muddy soaks
Temeira	50	80°	Siwa-Qara	Extensive areas of sabka and several salt lakes bearing sub-aqueous springs vents
Tebaghbah	90	95°	Siwa-Qara/Siwa Bahriya	Three springs along escarpment above sabkha
Areg	90	110°	Siwa-Bahriya	Vegetated depression containing several muddy soaks
Bahrein	106	123°	Siwa-Bahriya	Two salt lakes flanked by date palms and reed
Nuwemeisa	128	115°	Siwa-Bahriya	Salt lake flanked by date palms and reed
Sitra	140	111°	Siwa-Bahriya	Salt lake flanked by date palms and reed
Qara	104	65°	Siwa-coast/Siwa-Nile via Qattara Depression	Several active springs. Oasis contains salt lakes, sabkha and irrigated land from bores and springs

provided a ‘large supply’. In Bahriya, Ain Guffara provided a ‘good supply’ and watered ‘three small palmgroves’, while Ain Gharbiya irrigated ‘rice and wheat fields surrounded by drift sand’. In Farafra, Ain Kiffrein watered ‘a palm grove and five small gardens about 1 km from its source’ and Ain Bishoi provided a ‘good supply from a deep shaft timbered with palm and acacia wood’.

In Siwa and the remote oases, flowing springs and artesian bores, as well as salt lakes and sabkha formations fed by groundwater, have remained active and flowing due to their relative elevation below the piezometric head of the aquifer. Siwa suffers from an over abundance of water demonstrated by the abandonment of some springs in favour of bores as well as more disturbing trends including the expansion of naturally occurring salt lakes, as well as extensive patterns of water logging and salinisation compounded by the region’s brackish groundwater sources (Figs. 19 and 20).

Conclusion

The springs in the oases of Egypt’s Western Desert span the rise and fall of the great civilisations of the ancient world, from the Pharaonic dynasties to Persian, Greek and Roman conquest. The springs have been extensively modified throughout this rich history, but the introduction of new drilling methods and equipment in the modern era has seen unprecedented changes. The proliferation of bores throughout the 20th century led to rapid declines in aquifer pressure and the extinction of springs. Patterns of spring loss and land abandonment are visible across the Western Desert, but these changes were broadly ‘compensated’ for by the expansion of new farming settlements or the ‘rehabilitation’ of some ancient springs with new facilities. The ancient caravan routes, once supported by springs, have been replaced by highways and the motorcar. Further study of the economic and social impacts of spring

Fig. 16 Qara Oasis showing cultivated palms and salt lake in distance

Fig. 17 ‘Qattara’ or Tabaghbah Spring No. 3 consists of a limestone overhang dripping with salt water

Fig. 18 Ain Goz in Kharga Oasis is marked by a large mound and several dead palm trees

Fig. 20 Abandoned and heavily salinised agricultural land in Siwa Oasis. The *square plots* are former fields which are traditionally flood irrigated in the oasis

loss is warranted as well as a deeper investigation of falling water levels and extraction costs.

Current hydrogeological understanding asserts that following the last Holocene pluvial phase, the NSA entered a state of natural decline which has increased exponentially in the wake of recent desert reclamation schemes. The rapid disappearance of the springs was an early indication of the falling groundwater levels. The loss of flowing bores which followed and ongoing depletion of the NSA raise pertinent questions regarding the future economic prosperity and survival of the oases.

Fig. 19 Drain of Ain Estakherab in Kharga Oasis (source: Beadnell 1909)

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