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Mining Fossil Water: A Review of Groundwater Depletion, Recharge and Sustainable Management of the Nubian Sandstone Aquifer System

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Abstract

The Nubian Sandstone Aquifer System (NSAS), shared by Egypt, Libya, Sudan and Chad, is the largest fossil groundwater system on Earth, underlying about two million square kilometres of the eastern Sahara. Most of its water was recharged during humid periods of the Pleistocene and early Holocene and is effectively non-renewable on human timescales. Expanding abstraction for desert reclamation in Egypt's Western Desert and for Libya's Great Man-Made River has lowered water levels, dried artesian springs and raised pumping costs at major centres. This review synthesises hydrogeological, isotopic, numerical-modelling and satellite-gravimetry (GRACE) studies to assess the state of the aquifer. The literature agrees that large-scale transboundary drawdown is likely to be limited, but that local drawdown at pumping centres co-located with oases will become excessive, threatening oasis ecosystems, traditional agriculture and the economic viability of reclamation schemes. GRACE-based studies estimate depletion of about 4.4 km³ per year in the Dakhla sub-basin and show that modern recharge is episodic and limited to the southern and eastern margins during exceptionally wet years or high stands of Lake Nasser. The review discusses the economics of mining fossil water for low-value crops, the environmental impacts on oases, and the institutional arrangements of the Joint Authority for the Study and Development of the Nubian Aquifer, and proposes a framework for planned, transparent depletion management.

Keywords: *Nubian Sandstone Aquifer System; fossil groundwater; GRACE; groundwater depletion; recharge; Western Desert; Kufra; transboundary aquifer; desert reclamation*

1. Introduction

As surface-water supplies tighten across North Africa, governments have turned to deep groundwater as a strategic reserve. In Egypt, where Nile water is fully allocated and increasingly uncertain (see the companion review on the Grand Ethiopian Renaissance Dam in this issue), the Nubian Sandstone Aquifer System (NSAS) underpins national programmes to expand cultivation into the Western Desert, including the 1.5-million-feddan project and the East Oweinat, Toshka and Farafra schemes. In Libya, the Great Man-Made River conveys water from well fields at Kufra, Sarir and the Fezzan to coastal cities. In Sudan and Chad, the aquifer supports scattered rural communities.

The NSAS is often described as the world's largest fossil aquifer (Voss & Soliman, 2014). Its water is old: radiocarbon and chlorine-36 dating indicate ages from several thousand to several hundred thousand years, reflecting recharge during wetter climatic phases (Sultan et al., 1997). Present-day rainfall over most of the system is below 5 mm per year, so abstraction is largely a mining of stored water. The question is therefore not whether the resource is being depleted, but at what rate, with what local and transboundary consequences, and to what economic end.

This review summarises current understanding of (i) the aquifer's structure and hydrogeology, (ii) estimates of storage, recharge and depletion, including satellite gravimetry, (iii) environmental and socio-economic impacts of abstraction, and (iv) options for governance.

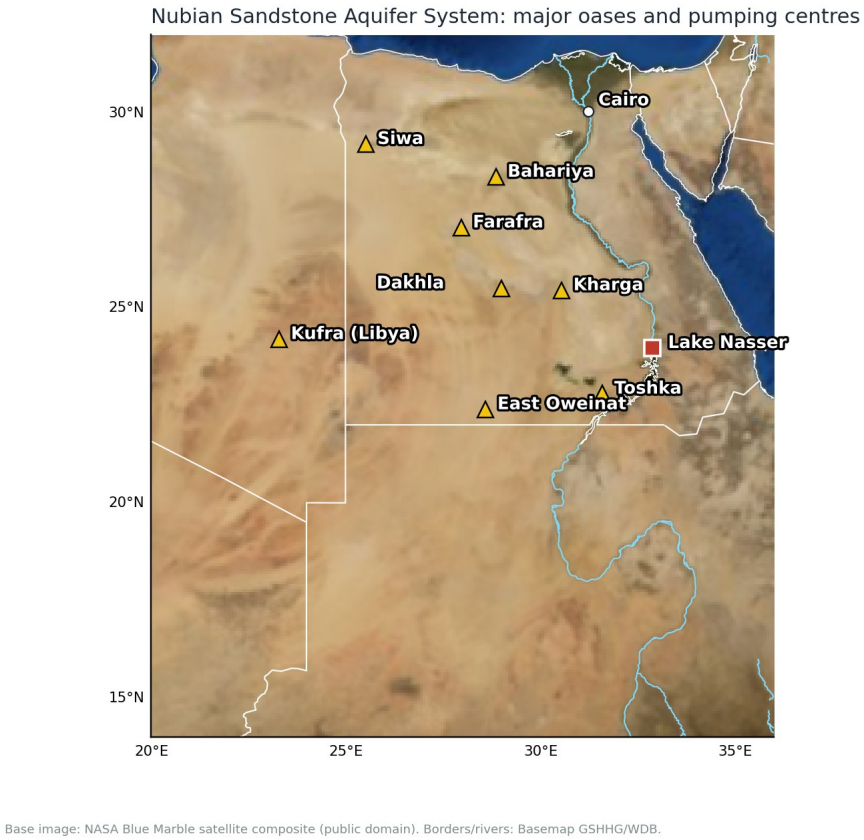


Figure 1. Satellite view (NASA Blue Marble composite) of the eastern Sahara showing the principal oases and pumping centres of the NSAS in Egypt (Kharga, Dakhla, Farafra, Bahariya, Siwa, East Oweinat, Toshka) and Libya (Kufra), together with Lake Nasser, which interacts with the aquifer along its eastern margin.

2. Hydrogeological setting

The NSAS covers about 2.2 million km², of which roughly 38% lies in Egypt, 34% in Libya, 18% in Sudan and 10% in Chad. It consists of continental and shallow-marine sandstones of Palaeozoic to Mesozoic age, interbedded with shales, resting on Precambrian basement. The system is unconfined in the south and becomes confined northwards beneath younger marine shales and carbonates, where it is overlain by the Post-Nubian aquifer. Thickness increases from a few hundred metres in the south to more than 3,000 m in parts of the Kufra and Dakhla basins.

Regional flow is broadly from south-west to north-east, from the higher ground of the Tibesti, Ennedi and Uweinat regions towards natural discharge areas in the depressions of the Western Desert (Kharga, Dakhla, Farafra, Siwa and the Qattara Depression), where artesian springs historically supported the oases. Major basement uplifts, notably the east–west Uweinat–Aswan uplift, divide the system into sub-basins (Kufra, Dakhla and the Northern Sudan Platform) with limited hydraulic connection (Mohamed et al., 2017).

Total freshwater in storage is estimated to be on the order of 10^5 km³, but the economically recoverable fraction, limited by drilling depth, pumping lift and water quality, is far smaller, and numbers that combine the two can be misleading for planning.

3. Recharge: how much modern water enters the system?

Isotopic evidence shows that most groundwater in the NSAS was recharged during the Pleistocene and early Holocene humid periods, when the eastern Sahara supported lakes and savanna (Sultan et al., 1997). Present-day recharge is debated. Satellite gravimetry from the GRACE mission, combined with land-surface models and precipitation data, offers a way to estimate changes in total water storage over large areas.

Using GRACE data for 2002–2016, Ahmed and Abdelmohsen (2018) estimated that the Nubian aquifer in Egypt received a total recharge of about 20.3 ± 2.0 km³ over the 2002–2006 and 2008–2016 periods, that recharge events occur only under excessive precipitation over the southern recharge domains or a significant rise in Lake Nasser levels, and that the aquifer experienced depletion of about 13.5 km³ per year during the exceptional 2006–2008 drought. Mohamed et al. (2017) estimated modern recharge of about 0.78 km³ per year in the southern Kufra section and 1.44 km³ per year in the Northern Sudan Platform sub-basin, where higher rainfall reaches the aquifer outcrop. Abdelmohsen et al. (2019) showed that even deep parts of the system respond rapidly to climate variability through pressure transmission. Lake Nasser is an important local source: when the lake is high, it recharges the adjacent sandstones, and when it falls, the flow reverses.

These findings indicate that the NSAS is not entirely fossil: small, episodic recharge occurs along its southern and eastern margins. However, recharge is concentrated far from the main abstraction centres in Egypt's Western Desert and Libya, and is small relative to planned abstraction.

4. Depletion: evidence from monitoring, models and satellites

4.1 Water-level declines at pumping centres

Since the 1960s, when the New Valley project began large-scale drilling in Kharga and Dakhla, artesian pressure has declined steadily. Many springs that flowed freely have ceased, and wells that once flowed under artesian pressure now require pumps, with water tables falling by tens of metres in the most intensively exploited areas. Similar declines have been reported around the Kufra and Sarir well fields in Libya.

4.2 Regional models

The joint IAEA–UNDP–GEF project on the NSAS developed a regional model with the participation of all four countries. The resulting analysis by Voss and Soliman (2014) concluded that transboundary drawdown is likely to be minimal and essentially a non-issue for international relations, whereas drawdown within pumping centres may become excessive, requiring alternative extraction schemes; they noted that significant water-table drawdown at pumping centres co-located with oases could cause oasis loss and environmental impacts. Earlier modelling by Gossel et al. (2004) reached broadly similar conclusions about regional water-level declines under increasing abstraction scenarios.

4.3 Satellite gravimetry

GRACE-derived terrestrial water storage provides an independent, if coarse, view of depletion. Mohamed et al. (2017) estimated groundwater depletion of about 4.44 ± 0.42 km³ per year over the Dakhla sub-basin and 0.48 ± 0.32 km³ per year over the northern Kufra section, and attributed the concentration of depletion in the southern Dakhla sub-basin to the Uweinat–Aswan basement uplift, which impedes south-to-north flow and hence replenishment from the recharge areas. An earlier GRACE analysis presented by the same research group identified significant storage loss of about 1.3 km³ per year correlated with the Dakhla Basin and concluded that excessive groundwater extraction, not climatic change, was responsible.

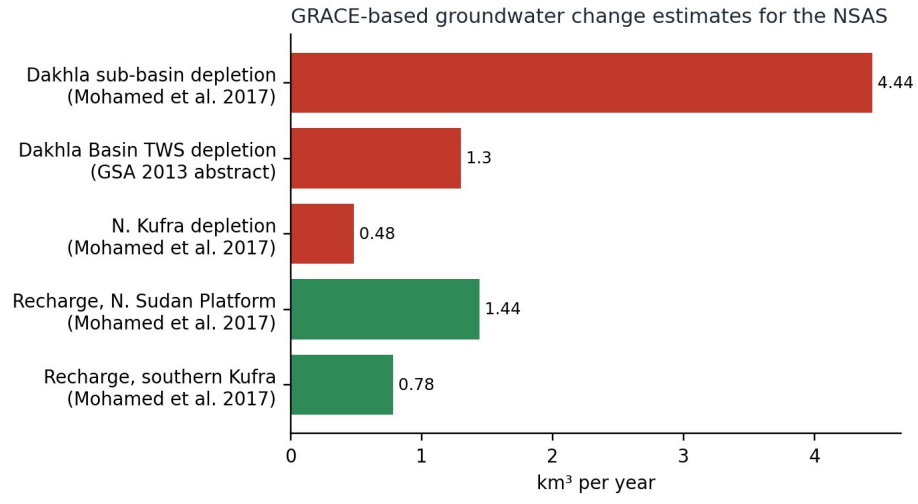


Figure 2. GRACE-based estimates of groundwater storage change in the NSAS from the studies reviewed. Depletion (red) is concentrated in the Dakhla sub-basin of Egypt's Western Desert; modern recharge (green) is concentrated in the southern recharge areas far from the main pumping centres.

The differences between these estimates reflect the study period, the land-surface models used to remove soil-moisture signals, and the treatment of Lake Nasser storage changes. Nonetheless, all GRACE-based studies agree that the Dakhla sub-basin in Egypt is losing storage and that this loss is driven by abstraction.

5. Environmental and socio-economic impacts

5.1 Oases and traditional agriculture

The most direct environmental cost of abstraction is the loss of natural springs and the wetlands they support. Oases in the Western Desert are cultural landscapes with date palms, olive groves and small irrigated plots sustained for millennia by artesian flow. As pressures fall, smallholders must deepen wells and install pumps, which increases costs and tends to favour large commercial operators. In Siwa, by contrast, the problem is excess drainage water: increased abstraction from the deep aquifer and inefficient irrigation have raised saline water tables and expanded salt lakes, waterlogging farmland. Both cases show that unplanned abstraction disrupts fragile oasis water balances.

5.2 Water quality

Water quality in the Nubian sandstones is generally good (low salinity), but iron and manganese concentrations are high in parts of the system, requiring treatment for drinking water, and salinity increases northwards in the confined section and in the Post-Nubian aquifer. Declining heads can induce upward leakage of more saline water from overlying formations or lateral inflow of poorer-quality water.

5.3 Energy and economics

As water levels fall, pumping lifts increase, and energy becomes the dominant operating cost. Much new pumping in the Western Desert uses diesel or grid electricity, although solar-powered pumping is expanding rapidly. The economics of reclamation depend strongly on crop choice: mining fossil water to grow low-value, water-intensive crops such as wheat, alfalfa or other fodder for export can be uneconomic once the full cost of the water, including its scarcity value to future generations, is considered. High-value horticulture, dates and olives with efficient drip irrigation generate far more value per cubic metre.

5.4 Land subsidence and soil salinisation

Large drawdowns can cause compaction of interbedded clays and land subsidence, as observed in other heavily pumped aquifers, although the NSAS sandstones are relatively incompressible. Irrigation with even modestly saline groundwater in closed desert basins without drainage outlets leads to salt accumulation in soils over time (see the review on soil salinisation in this issue).

6. Governance of a shared fossil resource

Egypt, Libya, Sudan and Chad established a Joint Authority for the Study and Development of the Nubian Sandstone Aquifer Waters in the early 1990s, and in 2000 agreed on procedures for monitoring and data sharing. The IAEA–UNDP–GEF project produced a shared aquifer diagnostic analysis and a strategic action programme signed by the four countries in 2013,

which identified priority threats including declining water levels, water-quality deterioration and the potential for transboundary impacts. Implementation has been constrained by conflict in Libya, Sudan and Chad, limited monitoring networks and the absence of binding abstraction limits.

Because the modelling evidence suggests that transboundary drawdown is limited, the more important governance challenge is domestic: deciding how fast each country wishes to deplete its share of a finite resource, for what purposes, and how the resulting benefits are distributed. Planned depletion is a legitimate policy choice for a non-renewable resource, but it requires explicit decisions about the planning horizon, the minimum reserve to be retained for drinking water, and the protection of oases.

Table 1 summarises recommended management measures drawn from the literature.

Table 1. Recommended measures for sustainable management of the NSAS

Measure	Purpose	Responsible level
Dense observation-well network with open data	Track drawdown and calibrate models	National agencies; Joint Authority
Annual GRACE-FO and InSAR assessments	Independent regional storage and subsidence monitoring	Research institutions
Abstraction licensing with metering	Limit drawdown at pumping centres	National water ministries
Spacing of new well fields away from oases	Protect springs and traditional agriculture	Planning authorities
Crop restrictions favouring high water productivity	Maximise economic return per m^3 of fossil water	Agriculture ministries
Reserve for drinking water	Secure long-term municipal supply	National policy
Solar pumping with demand caps	Reduce energy costs without encouraging over-pumping	Energy and water ministries
Regional data exchange	Detect any transboundary effects early	Joint Authority

One caution deserves emphasis. Solar-powered pumping removes the marginal energy cost of abstraction and, without metering and quotas, can accelerate depletion, as has been observed in other regions. Subsidies for solar pumps in the Western Desert should therefore be linked to enforceable abstraction limits.

7. Research priorities

Key gaps include: (i) a public, harmonised water-level database for the whole system; (ii) updated three-dimensional models that incorporate the actual abstraction of the past decade, including the new reclamation schemes; (iii) improved separation of groundwater, soil-moisture and Lake Nasser signals in GRACE and GRACE-FO data; (iv) quantification of modern recharge using isotopes and remote sensing; (v) economic analyses of the opportunity cost of fossil water under alternative crop and energy scenarios; and (vi) ecological baselines for the spring-fed wetlands of the oases.

8. Conclusions

The NSAS is a vast but finite resource. The scientific literature converges on three conclusions. First, groundwater in Egypt's Western Desert, particularly the Dakhla sub-basin, is being depleted at rates of the order of several cubic kilometres per year, driven by abstraction rather than climate. Second, modern recharge is real but small, episodic and located far from the main pumping centres, so it cannot sustain present abstraction. Third, transboundary effects are likely to be modest, whereas local effects on oases, water quality and pumping costs are already significant. Treating the NSAS as a strategic reserve, depleted deliberately and transparently for high-value uses, with strong protection of oases and drinking-water supplies, would allow North African countries to benefit from fossil water without exhausting it for low-value crops.

Declarations

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