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TITLE PAGE

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Abstract

Strategies for managing water stress negotiate a complex series of trade-offs and opportunities. Game-changing opportunities for water stressed regions are emerging with new emissions reduction strategies and energy options. These have particular significance for socio-economic development pathways in the marginal drought-prone regions. In this paper, we explore the energy–water–environment nexus in watersheds undergoing acute water stress and energy transitions in the Arab region and the Horn of Africa. A review of published and ongoing scientific activity was used to elaborate four case studies and identify common trade-offs between objectives to reduce water stress, increase productivity and lower energy costs and emissions. The available scientific evidence base for assessment of these trade-offs was then compared via a discursive process amongst review team members.

Collectively, the case studies present a State of the Art in geoscientific research priorities and methods currently applied in the Arab region to quantify nexus trade-offs for decision-making concerning increasing groundwater use, water harvesting and wastewater reuse across the case studies. The review pursues the wider geographic relevance and scope of this emerging scientific agenda. It identifies global opportunities to boost and progressively enhance the geoscientific information bases for decision-making in the most water stressed regions, as well as direct comparisons to emerging discussion in the Horn of Africa region. Insights for sustainable development decision-makers are highlighted and further scope for the transfer of insights within and beyond the Arab region are discussed.

Keywords

Water, energy, water stress, drought, trade-offs

1. Introduction

Strategies for management of water scarcity negotiate a complex system of trade-offs between water, energy, and production of environmental services including food (IPCC 2018). Transitions in the use of energy technologies can boost water supplies in water-stressed environments (IEA 2016). But increasing emissions associated with many such technologies further exacerbate climate change and threaten resource-dependent populations (IPCC 2018; WWDR 2014). Analyses of trade-offs at the water–energy–food security nexus have invited decision-makers to rethink water resource development strategies that create bloated blue water and emissions footprints in many regions (Endo et al. 2017; Hoff 2011). A range of such analyses have been generated in the Arab Region (Amer et al. 2017; Daher and Mohtar 2015; ESCWA 2016; Hoff et al. 2017), and parts of sub-Saharan Africa (IUCN 2015; Jillo et al. 2016; Wakeford 2017; Yang et al. 2018)[1]. This paper emphasizes the implications of energy and emissions trade-offs as a critical entry-point to managing the nexus (i.e. *Energy*-Water-Environment trade-offs) associated with water management adaptations in the most drought-prone and water stressed regions.

Increasing surface water shortages and dependence on groundwater to meet domestic, irrigation and other water demands is a growing concern in many of the worlds dry regions (Cherlet et al. 2018; Kaur et al. 2016). Pumping groundwater is about seven times more energy intensive than surface water abstraction (UNWater 2018). On the other hand, in some cases, surface water requires more (energy-intensive) treatment prior to use than groundwater (IEA, 2016a). Many millions of impoverished smallholder farmers across the drylands of sub-Saharan Africa and Asia are reliant on groundwater due to its relatively good quality, ease of access, reliability and flexibility (Shah, 2012). But over-extraction of groundwater can have disastrous effects on environmental sustainability (Giordano and Villholth 2007; Velis et al. 2017; Villholth et al. 2017). In many parts of the Arab region, these problems are advanced, and national strategic and scientific capacities are increasingly engaged to address the challenge. This is generating knowledge and insight that is of value to global environmental debates beyond the agricultural sector of the Arabian region.

Global interest in the extent and significance of trade-offs and synergies at the land-water-energy nexus in highly water-stressed contexts is increasing (IPCC 2018; Velis et al. 2017). Geoscientific investigations can shed light on the stakes involved, and more will be required over the coming years. In this paper, we revisit a previous

[1] see also: https://www.water-energy-food.org/resources/resources-detail/nexus-country-profiles-for-the-niger-basin/

analysis of nexus trade-offs in the Arabian region (King and Jaafar 2015) and extend its scope to consider similar nexus challenges and trade-offs in the drought-prone Horn of Africa. A simplified resource-accounting approach (after UN and FAO 2014) is used to characterize effects on the production of ecosystem services for human well-being associated with different land management technology alternatives and scenarios, based on the information available in each case. Ecosystem services include food production but can also encompass a range of other products and services. The simplified resource accounting approach enables analysis of tradeoffs between effects on water availability and energy consumption required to produce these services.

The objectives of this paper are to:

- Identify the critical choices concerning energy technologies, costs and implications for balancing water stress in the selected water stressed basins;
- Explore the current state of geoscientific knowledge and tools to support decision-makers' assessments of trade-offs between available technological options to balance basin-level water stress and objectives to reduce emissions and energy costs while maximising services to human well-being;
- Consider the relevance of these insights from geoscientific work in the Arab region for other water stressed contexts, including those in other drought-prone regions, particularly in Africa.

These objectives are reflected in the organization of the paper. A brief description of the approach and methods used to identify the critical choices concerning energy technologies, costs and implications for balancing water stress in the selected water stressed basins is presented in Section 2, and the four case studies are presented. In Section 3. the trade-offs for sustainable development decision-makers emerging from each of the four case studies are reviewed. Three common trade-offs are identified and discussed. These include increasing demands for energy due to growing dependence on groundwater in the drier regions; the potential of water harvesting and groundwater recharge techniques to slow the increasing demand for energy; and additional trade-offs associated with increased recycling of water. The discussion in Section 4 focuses on knowledge gaps and opportunities for further geoscientific investigation to boost and progressively enhance the information base for decision-making at this critical nexus. The conclusion in Section 5 underlines the broader relevance of geoscientific insights already gained in the Arab region for other water stressed basins in other regions, particularly in Africa.

2. Approach and methods

2.1 Case Studies

Four basins were selected for discussion as case studies in this article (Table 1). These included a case from the drought-prone Horn of Africa region, as well as three water-stressed basins from the Arab region where geoscientific work has been accelerating over the past few years (as evidenced by an earlier review in King and Jaafar 2015). In each case, transitions are taking place due to increasing water demands and groundwater extraction rates. Based on information available as of early 2018, a rapid review and assessment was made to identify what is presently known or can be inferred about effects on economic production, water stress, energy use and emissions in these four cases, including consideration of available technological options to adapt the current land and water management patterns and scenarios.

Table 1: Selected case study areas and basins

Study area	**Extent (km^2)**	**Basin / watershed**	**Countries**	**Total Extent** (1000 km^2)
Koutine Watershed	279	Koutine Watershed	Tunisia	0.279
Bekaa Valley	170	Orontes Basin	Lebanon, Syria, Turkey	37.900
Isiolo County	25,336	The Ewaso Ng'iro North Catchment Area	Kenya	210.226
Nile Delta	25,000	Nile Basin	11 countries	3173

(Figure 1: Location of case study areas and basins)

2.1.1 Case of the Ewaso Ng'iro North Catchment, Kenya

The Ewaso Ng'iro North Catchment Area (ENNCA) (surface area: 210,226 km^2) (Figure 1) is the largest and most arid catchment in Kenya (WRMA 2014). Beyond Kenya, the catchment continues into the bordering areas of Ethiopia and Somalia, where it forms part of the larger Juba-Shabelle basin[2](total basin area: 749 000km^2). The Dawa river (58,961km^2) forms the border between Kenya and Ethiopia. It joins the Juba River at Dolo, where it then becomes the Somalia-Ethiopia border (Basnyat and Gadain 2009; Woldemariyam and Ayenew 2016a; Woldemariyam and Ayenew 2016b). Although much of the flow from Kenya into Somalia is in the subsurface Merti aquifer system (GIBB 2004; Oord et al. 2014), a seasonal tributary known as the Lagh Dera also joins the Juba river in Somalia (Michalscheck et al. 2016).

The upstream flows through ENNCA are reducing because land and water management decisions in the highlands around mount Kenya are resulting in loss of forest cover and increased water extraction for commercial agriculture (Mutiga et al. 2010; WRMA 2013a). This is progressively reducing flows of water to vulnerable populations downstream and also reducing natural flow regulation. This results in increased water stress in the downstream areas during dry seasons, interspersed with disastrous floods that cause economic damage and sometimes loss of human life in urban areas during rainy seasons (GoK 2014; King-Okumu et al. 2017).

Water managers have observed that the upstream extractions contribute to the economy, and are difficult to prevent - even if they are illegal (Mutiga et al. 2010). Instead of regulating and conserving the flows of surface water, the national water masterplan for the downstream areas focuses on increasing the use of groundwater to supply the downstream populations (WRMA 2013a; 2013b; 2014; 2016a; 2016b). This has implications for energy demand (Harou et al. 2017; King-Okumu et al. 2018). The expansion of water and energy services to improve living standards for the urbanizing downstream populations must rely either on increased use of diesel fuel to pump water, or on renewable energy, such as solar and wind power (Ndirangu 2017). In ENNCA, since the availability of water flow throughout the year is already too low to support hydropower development, this is not an option. However, Kenya is investing heavily in electricity transmission lines to import hydroelectricity from neighbouring Ethiopia (Wakeford 2017).

[2] See: http://sddr.faoswalim.org/River_atlas/atlas/River_Atlas_Som_Part1_drainage.pdf

2.1.2 Case of the Nile Delta, Egypt

The Nile Delta extends over around 2,500,000 ha, with maximum annual rainfall of around 200mm at the coast, and less inland. The cultivated area of the delta is supplemented by ongoing land reclamation. The annual volume of surface water inflow at the High Aswan Dam is 55.5 km^3/y, and annual outflow to the sea, 12.2 km^3/y (MWRI 2010). Under climate change and upstream development, the volume of water reaching the Delta from the Nile Basin (Figure 1) will be reduced.

A recent assessment of the water balance in the Nile Delta (Molle et al. 2016; 2018) found that thanks to the reuse of drainage water, despite increasing volumes of water use, and reduced inflows, the outflows to the sea had remained relatively unchanged since the 1990s. Water demand for drinking in Egypt is 1.8 km^3/y, while industry requires 1.4 billion m^3 (MWRI 2010). The amount of water used by the agricultural sector in 2010 was about 67 km^3/y, including leaching requirements and deep percolation to shallow groundwater. To achieve this, and support other sectors, other water sources are used besides surface water. These include deep non-renewable groundwater sources as well as the reuse of drainage water. The major uncertainty concerns the volume of groundwater use across the various sectors, including agriculture and others (including municipal and industrial uses). Water quality challenges including salinity and others are an increasing concern.

At present, the agricultural sector is estimated to be responsible for 85% of water demand in Egypt, but only 5% of its energy demand (Hoff et al. 2017). These estimates may require further geoscientific investigation. Based on emerging observations of the extent of shallow groundwater reuse in the Delta and the surrounding reclamation areas (El-Agha et al. 2016; King and Salem 2012; 2013; Molle et al. 2018), it appears likely that current estimates of agricultural energy uses may already be underestimated. Irrigation practices can help to increase economic water-use efficiency, but this often creates further increased demand for energy to control the water application (King and Jaafar 2015). Furthermore, the majority of high value horticultural crops that are sufficiently profitable to pay for such systems require irrigation with fresh water, which must still be pumped from deep underground.

2.1.3 Case of the Upper Orontes, Lebanon

The total area of the Orontes Basin is 37,900 km^2, including parts of Lebanon, Syria and Turkey. Lebanon's Beka'aa Valley covers 17,000 ha at the upstream end of the basin and receives average annual rainfall of 150mm (total volume: 25MCM/y) (Figure 1). The agricultural land cover visible in summertime has expanded by more than 20% on average since the beginning of the century, mainly in areas not served by the existing open-channel irrigation scheme, but irrigated using groundwater (Jaafar and Ahmad 2019 in press; Jaafar et al. 2015; Saadé-Sbeih et al. 2018).

At present, the energy uses for pumping additional groundwater in the hotspots of water stress are identified as a concern in Lebanon's third national communication to the UNFCCC, which predicts that in the future (MoE/UNDP/GEF 2016 pXII): 'Droughts will occur 15 days to 1 month earlier, and countrywide drought periods will extend 9 days longer by 2040 and 18 days longer by 2090. The already dry regions, such as the Bekaa, Hermel, and the South, will experience the sharpest effects. In addition, cost impacts will be added to irrigation needs, as more pumping hours will be required, therefore consuming more energy.' Where surface water is not available to meet human needs, groundwater is increasingly used (BWE 2015; Jomaa et al. 2015). Water table levels in the Bekaa are falling (MoEW/UNDP 2014). A drop of about 20m since 1970 (average of 60cm/year) has already been observed in the neighbouring Litani area in the Southern Bekaa Neogene-Quaternary Basin. In some parts of the Bekaa, the water table has fallen by more than 15m over the last five years (Jaafar and Ahmad 2019 in press).

Recently, Jaafar et al (2016) examined the water balance in the upper Orontes, and identified the need to consider a more comprehensive range of sectoral water uses and demands affecting water and energy dynamics – not only those of agricultural water uses which have been the focus of previous nexus studies (e.g. King and Jaafar 2015). The analysis responded to popular concerns that population growth since the arrival of refugees from Syria may be creating new water and energy access challenges, and exacerbating climate and drought risks (MoE-EU-UNDP 2014). However, investigation of the additional water demands for the refugees (Jaafar 2017) showed that these were still relatively small compared to the agricultural water use volumes. Nonetheless, the spatial and temporal concentration of the demand peaks were creating hotspots of water stress. This was accelerating groundwater extraction and therefore creating additional energy demands due to the increases in pumping depths to groundwater (Jaafar et al. 2016).

2.1.4 Case of Zeuss Koutine Watershed, Tunisia

Several ephemeral rivers feed the Zeuss Koutine Aquifer in the Koutine Watershed, Tunisia (Figure 1). Traditionally, in the upper reaches of the Koutine Watershed, rainfall and water-harvesting structures (known as *jessour*) support agroforestry, intercropping of barley and natural vegetation for grazing by livestock. Further down, in the plain, water-harvesting structures are known as *tabia*. Harvesting rainwater to support trees and fodder for livestock can simultaneously increase the recharge of groundwater (2009; Ouessar et al. 2004). Where rainwater captured in the soil profile exceeds the water holding capacity, it will percolate downwards and recharge the groundwater reserves flowing through the Zeuss Koutine Aquifer, serving the downstream urban population in the cities of Medenine, Tataouine, Jarzis, Djerba and Benguerdene. The water demands of these cities are growing rapidly and outstripping the available supplies of freshwater.

There are two main aquifers: the Zeuss Koutine aquifer and the Gres de Trias aquifer both supply domestic water use, tourism, industry and commercial uses. A third aquifer is the saline Jeffara aquifer. The main source of water for the agricultural sector are shallow aquifers supplemented mainly by water from the Zeuss Koutine aquifer and also occasionally to a lesser extent by the Gres de Trias aquifer. Recently a desalination plant was constructed purifying water from the brackish Jeffara aquifer to supply to the urban consumers in Djerba/ Zarzis and for the tourism sector. An additional seawater desalination plant (capacity: 50.000 m^3/day) was partially operational in 2018 to supply water to the same users. With these developments, pressure on the two aquifers is expected to diminish and plans are underway to develop additional irrigated areas using the conserved water from these aquifers.

A previous rapid assessment (King and Jaafar 2015) focused on exploring how water harvesting could help to meet urban water demands and reduce the need for energy-intensive and expensive desalination and water transfers in urbanizing catchments such as the Zeuss Koutine watershed. This was based on the view that farmers' use of water harvesting upstream could enhance groundwater recharge and affect the availability of water downstream. This could help to avert the need for increasing use of expensive and energy intensive desalination facilities to supply water to the downstream urban areas of Medenine. However, in light of increasing demand, reliance on desalination has grown over the past years. Water harvesting may substitute for some of the requirements for desalination. But if the population continues to grow and remains concentrated in the coastal cities, demand for desalinated water is likely to continue to increase.

2.2 Methods for the characterisation of energy-water-environment trade-offs

Trade-offs of interest in this review concern the available technological options to balance basin-level water stress and objectives to reduce emissions and energy costs while maximising services to human well-being. These were identified through a review of published literature and ongoing field studies. This built on and extended a previous review of the three Arabian cases (presented in King and Jaafar 2015). The addition of a case from the Horn of Africa region draws on a body of work by practitioners from that region (Jarso et al. 2017; Jillo et al. 2016; King-Okumu et al. 2018). This sheds light on the wider relevance of the adaptation options under discussion, and of the ongoing geoscientific investigations needed to assess the associated trade-offs.

A series of common adaptations to water stress were identified amongst the case studies. Their effects on energy use and emissions, and the production of services for human well-being were weighed against the anticipated effects on water stress. This assessment drew on relevant published or ongoing geoscientific work, where available to create a simplified representation of a resource-accounting approach (after UN and FAO 2014). The assessment was presented qualitatively as positive and negative directional indicators. This reflected what is known regarding the characterisation of opening balances, inflows, storage, products, and outflows of water, energy and geochemicals associated with different land management technology scenarios (as explored previously for the three Arabian cases in King and Jaafar 2015). The simplified presentation facilitated discussion and comparison between cases.

The format for presentation and discussion of the trade-offs in this paper is similar to those used in the future scenarios of the millennium ecosystem assessment (Carpenter et al. 2005), IPCC reports (IPCC 2018) and popular assessments of sustainable land management strategies (WOCAT 2013). This could be intelligible to decision-makers and non-specialists as well as to researchers. It provides a simple indication of the direction of change as either positive or negative. The categories of impacts considered are broad: combing effects on energy use and emissions. Impacts on the production of services for human well-being is also a broad category of impacts that includes consideration of effects on the production of food as well as other services that require water and ecosystem management.

An iterative discursive approach to the review of the available information concerning the nexus trade-offs encourages reflection by researchers and decision-makers. A preliminary version of the assessment was presented and discussed during an international conference on Water, Environment, Energy and Societies, held in Zarzis, Tunisia, in May, 2018. This was supplemented by continuous iterative review and progressive update by members of the research team. In this way, the review takes into consideration gradual advances in the availability of geoscientific studies relevant to understanding the nexus trade-offs. It also enables reflection on remaining gaps and research priorities.

The iterative development and comparison of the four case studies revealed three common trade-offs associated with adaptation to water stress. These concerned:

- increasing costs and carbon emissions to pump greater volumes of groundwater from depleting groundwater tables
- slowing the increases in groundwater pumping costs and emissions by recharging water tables (with different implications for energy requirements)
- increasing water availability by recycling and treating wastewater (with a range of possible implications for energy use)

Based on this characterisation of the common concerns and challenges amongst the case studies, it was possible to identify gaps in the available geoscientific knowledge base, and common priorities for further review and assessment.

2.3 Accounting for water management effects on energy use

In all four of the study areas, increasing reliance on groundwater and falling water tables are reported to have increased groundwater pumping costs. Previous studies have demonstrated and quantified these effects in Tunisia (Croitoru et al. 2010), parts of the Nile Delta (King and Salem 2013), and also in ENNCA (King-Okumu et al. 2018). Quantitative assessments of energy demands and costs for pumping groundwater for the Bekaa valley case study could not be identified through the review of published literature. However the problem of the escalating costs is mentioned in Lebanon’s third national communication to the UNFCCC, as referred to in the previous section (MoE/UNDP/GEF 2016 pXII). A rapid review of the available strategic documents from this and the other three cases suggests that the increases in carbon emissions of escalating groundwater pumping may not yet have been fully assessed in any of the cases.

In Lebanon, the emissions from combustion of fossil fuels for water pumps for agriculture are assumed to be relatively small compared to those of the other sectors, reaching a total of only 245Gg CO2eq (MoE/UNDP/GEF 2016; MoE/UNDP/GEF 2017). But this is significantly higher than other calculated emissions from the agricultural sector (other than nitrogen emissions from soil)(MoE/UNDP/GEF 2015a). The national reports on emissions calculations for agricultural lands were made using a methodology (based on IPCC 2003; MoE/UNDP/GEF 2015b). At the time of writing, these methods were under review and revision through the IPCC expert process. National and basin-level assessments may soon be able to consider the scope for updates and refinements (see: https://www.ipcc-nggip.iges.or.jp/public/index.html).

For estimating the amounts of energy required to pump the water used in agriculture, basic methods applied previously in Egypt (Attia et al. 2005; ESCWA 2009; Fraenkel 1986), were identified through the review of previous studies. Further methodological contributions were also identified from geoscientific studies published from India (Kaur et al. 2016), due to rising concerns that have emerged in groundwater dependent areas of that country. The following equation can be applied (after Kaur et al. 2016):

$$\text{Energy E, kWh} = \frac{m^{*}g^{*}h}{3.6^{*}10^{6}{}^{*}\eta_{\text{eff}}(\%)^{*}(1\text{-T}\&d\ \text{losses}(\%))} \qquad \text{(equation 1)}$$

Where:

E is the energy required to lift water in kWh;

m is mass of water pumped;

g is acceleration due to gravity 9.8 m s_2;

h is the total dynamic head, which is a function of initial water level, drawdown, delivery head and losses in pipe) and is calculated as per Equation (2) (Michael et al. 2008):

h = initial water level (m)

+ 20% of initial water level (m)

+ 5m (drawdown + delivery head) (equation 2)

Given the lack of detailed knowledge of the efficiency of individual pumps, Kaur et al (2016) recommended a value of around 30% based on available studies of energy use for irrigation pumping conducted previously in India (Nelson et al. 2009). Overall efficiencies in diesel-powered pumping systems result from the compounded efficiencies of the diesel engine (typically 15–40%), transmission (60–100%), pump (40–80%) and pipes (30–95%), giving an overall efficiency of 0.5–27% (Fraenkel 1986). Therefore, an approximate midpoint of 15% has been used in previous studies (Shah 2009).

Kaur et al (2016) used the all-India average value of 1.4 kg of CO2 kWh^{-1} at the station (0.406 kg C kWh^{-1}) to estimate the release of C from electric pumps. With 5% transmission losses, an effective C emission rate of 0.427 kg C kWh^{-1} at the generating facility or 3.87 kg C to lift 1000 m^3 to 1 m was used. The emissions from coal-based electricity power generation plants are about 5.82 (3.87/0.665) times higher than the rate of emission with diesel pumps (Nelson et al. 2009). With diesel pumps, the amount of C released to lift 1000 m^3 of water to 1 m is 0.665 kg C (0.732*9.08/10.0). The ratio of C emissions to energy content for diesel is 0.073 kg C kWh^{-1} (Nelson and Robertson 2008).

The energy and emissions associated with pumping water must be multiplied by the volume of water required, and the pumping depth. Other studies have used a mixture of remote sensing and ground-truthing techniques to identify the proportion of cropped land in the Bekaa that is irrigated, the wells and depths to water and the volumes of water required (Jaafar 2017; Jaafar and Woertz 2016; Jaafar et al. 2015). This information was used to complete the estimations of energy use and emissions in the Bekaa Valley (Table 2), based on a simplified application of Kaur's equations. For this study, the total annual irrigation water demand in the Bekaa for 2016 was estimated at 571MCM and the average depth of pumping around 100m (Jaafar 2017). For the other case studies, estimates of pumping costs were available from previous studies. In all cases, further refinements could be made.

Table 2: Estimation of total C emissions to lift groundwater each year (2016-2020) in the Bekaa Valley

		2016	2017	2018	2019	2020
	total volume of water lifted (mcm)	571	571	571	571	571
	volume of groundwater lifted assuming 65% of total is from groundwater (mcm)	371.15	371.15	371.15	371.15	371.15
a	volume of water (1000 m2)	371,150	371,150	371,150	371,150	371,150
c	amount of C released to lift 1000 m^3 of water to 1 m (kg C)	0.665	0.665	0.665	0.665	0.665
	a x c (kg C)	246,815	246,815	246,815	246,815	246,815
b	average depth (m)	100	100.6	101.2	101.8	102.4
	Total C emissions to lift groundwater a x b x c (kg C / yr)	**24,681,475**	**24,829,564**	**24,977,653**	**25,125,742**	**25,273,830**

Alternatives to increasing water supply via additional pumping of groundwater or other means include water conservation and recharge (to slow the demand for water). The extent to which this will slow demand for additional pumping and emissions depends on the volume of additional water that can be recharged. This is calculated based on the volume of rainfall, and context-dependent factors determining the proportion of this water that can infiltrate the soil and percolate down into the aquifer at different locations. The reuse of water presents a second alternative to increasing pumping of groundwater. How much energy is required to treat and reuse different volumes of water is determined by context and interrelated costs. In the case of Zeuss Koutine, rapid quantitative estimates were obtained to explore and illustrate the potential trade-offs that could be associated with these two options.

3. Energy-water-environment trade-offs under water stress

For review and comparison of the common trade-offs, in this section, the findings from the assessment of the available mix of quantitative and qualitative information is presented in a simplified format. This provides a simple indication of the direction of change as either positive or negative. This presentation device supplements the descriptive text exploring the trade-offs, as observed in each of the various case studies.

3.1 More water use: more energy for deeper groundwater pumping

In all four of the study areas, increasing reliance on groundwater and falling water tables are reported to have increased groundwater pumping costs. Previous studies have demonstrated this in Tunisia (Croitoru et al. 2010), parts of the Nile Delta (King and Salem 2013), and also in ENNCA (King-Okumu et al. 2018). To our knowledge, the consequences of this trend for increasing carbon emissions have not yet been fully calculated in any of the case study areas. Therefore, these may not yet be fully represented in the national emissions inventories and decision-making scenarios for future planning.

Where the water balance is exceeded, and water tables are falling, the depth of pumping will also increase – resulting in further increases in extraction costs and emissions (Table 2). As irrigation requirements and durations increase due to climate change, the total volume of water demand will increase further. Growing domestic, commercial and industrial water demands in the Bekaa will also contribute to the increasing extractions of groundwater. These require additional attention.

The methods that have been used to calculate the emissions from pumping groundwater for irrigation in the Bekaa valley could be refined further, as they could in all of the cases. However, it is notable from observations of the nexus in some of the other cases included in this review that there are ways to reduce the energy trade-offs associated with increased groundwater pumping. These require some additional consideration because they would affect the calculation of total energy costs and emission in all four of the cases.

According to Egypt's 3rd National Communication to the UNFCCC (MoE 2016), the national water infrastructure system in Egypt is mainly composed of irrigation, drainage, water and wastewater pumping stations, in addition to the water and wastewater treatment facilities. Potential for GHGs emissions mitigation opportunities include solutions for pumping, irrigation control and drainage. For these, considered options include replacement/rehabilitation of inefficient pumps and increased use of renewable energy sources. This is in addition to adaptation options involving water harvesting and reuse of non-conventional water sources. For the time being, scenarios for the potential impact and trade-offs of these adaptation options have not been quantified. However, recently, Egyptian researchers have begun to investigate the energy footprint of agricultural water management (El Gafy et al. 2017a; El Gafy et al. 2017b).

In the case of Egypt, mains electricity has been made available as a more cost-efficient option for pumping groundwater than diesel. The government has made access to this lower-cost energy source conditional upon having a legal permit for water extraction (King and Salem 2012). Furthermore, interestingly, in some areas, solar-powered systems are becoming more widely used for groundwater pumping and control of drip irrigation (AbouKheira 1999; IFAD 2016). Similarly, in ENNCA, 70% reductions of operating costs associated with pumping groundwater in the middle section of the catchment have been reported over the period 2013-17 due to conversion of boreholes from diesel to solar power (GoK 2018). These variations in the types of energy that are used for pumping groundwater will affect both the costs of pumping and the emissions that are produced (as explained in the previous section).

In contrast to mains electricity systems that are used to power deep groundwater extraction in some of Egypt's desert reclamation areas, solar-powered systems are not necessarily controlled or monitored easily by the government, and once installed, they can have lower recurrent costs than diesel-powered systems (Shouman et al. 2016). As yet, Egyptian farmers only use these systems to generate power for their own agricultural water management uses and are not able to sell it to local consumers or to the national grid (IFAD 2016). However, in 2014, Egypt passed a law promoting the use of renewable energy[3]. The Law encourages the private sector to produce electricity from renewable energy sources by introducing several development schemes for the private development of renewable energy projects, including competitive bids, feed-in tariff, and independent power production through third party access. Similarly in Kenya, private sector participation in provision of solar-energy powered systems for boreholes and irrigation is sought through public-private partnerships (GoK 2018 p141).

The Egyptian government has observed that advances in the capacities of solar-powered technologies to pump increasing volumes of deeper groundwater in the reclaimed desert areas could accelerate extraction and degradation of non-renewable deep groundwater supplies. They have therefore taken control of the solar-powered pumping systems in the desert areas. An alternative tried in India, but still unexplored in any of the case studies, would be to create markets for farmers to sell energy generated through solar technologies back to the national

[3] Renewable Energy Law (Decree No 203/2014) see: http://egyptera.org/Downloads/Laws/law2014.pdf

grid (as described in Shah et al. 2017; Verma et al. 2018). If the sale of energy becomes more profitable than the markets for the irrigated crops, farmers with access to technologies to capture solar energy may prefer to do this rather than to over-extract and damage their own collective water supplies by increasing water use for irrigation.

The various adaptations of systems for pumping groundwater each has different trade-offs for the production of food and other services to human well-being, as well as for water security and emissions reduction (Table 3). In the case from the Bekaa, we can see that increasing irrigated crop production has come at a cost to water security for other uses and has also raised emissions. On the other hand, in Kenya, where boreholes operated by rangeland water resource user associations have been converted from diesel to solar power, this has enabled the WRUAs to provide more reliable services to their members, while also reducing emissions. But this may still come at the cost of an increasing groundwater deficit, as is also the case in Egypt.

Table 3: Trade-offs associated with groundwater pumping and energy options

Adaptation	**Service production $**	**Water security**	**Emissions reduction**
Increasing groundwater extraction with diesel (Bekaa)	↑	↓	↓
Conversion of existing diesel-powered systems to solar power (ENNCA)	↑	↓	↑
New wells with solar-powered pumps (Western Desert, Egypt)	↑	↓	↑

↑ positive effect

↓ negative effect

3.2 Water harvesting and recharge: slow increases in energy needs for pumping

In Southern Tunisia, the Bekaa Valley and Northern Kenya, adaptation options involving water harvesting and groundwater recharge have been identified to achieve positive effects on service production, including provision of water supplies to reduce water stress (Table 4). In Egypt, similar options have been explored in the Northern Coastal areas, where there is relatively higher rainfall (Salem 2014). In Southern Tunisia (Ouessar et al. 2009) and in ENNCA (Gies et al. 2014), the effects of water harvesting structures on service production and income generation have been modelled using Soil Water Assessment Tools (SWAT). However, effects on groundwater recharge, labour and energy demands are still poorly understood in both cases. Even less geoscientific work has been published on such questions concerning water harvesting and groundwater recharge practices in the Bekaa and Egypt. On the other hand, in these areas, groundwater recharge associated with irrigation water application has attracted some scientific attention (see following section).

Table 4: Trade-offs associated with water harvesting and storage options

Adaptation	**Service production $**	**Water security**	**Emissions reduction**
Micro-catchments (Bekaa)	↑	↑	↑
Water pans and sand dams (ENNCA)	↑	↑	↑
Underground cisterns (Egypt N. Coast)	↑	↑	↑
Bunds and terraces (Koutine watershed)	↑	↑	↑

↑ positive effect

↓ negative effect

The human labour-intensity of construction and maintenance required for water-harvesting systems is often seen as a major constraint to their uptake by private landholders (Abdeladhim et al. 2017). In cases where water harvesting will simultaneously boost tree and forage production, this provides some incentives for land-users to implement the water harvesting practices. However, the income generation from trees and forage crops that can be supported through the water harvesting systems is not always considered sufficient to repay the labour investments required to construct and maintain them. In some cases (see e.g. : http://www.vallerani.com/wp/?tag=wocat-2), heavy machinery can reduce the costs of human labour required for the construction of water harvesting systems. As yet, such cases are not common in any of the study areas but investments in promoting such technologies are periodically discussed in international initiatives. The effects in terms of increasing emissions have not yet been assessed.

Since increasing groundwater recharge can improve water availability and quality downstream, in theory, downstream water users could be asked to pay upstream farmers for providing water harvesting services to them. At present, the Tunisian government provides support for conservation of water harvesting structures in the upper parts of the Zeuss Koutine water catchment. However, these incentives are still not enough to make water harvesting profitable for the farmers to build and maintain the systems. In all cases, it is difficult to convince downstream communities to provide incentives for improved water harvesting in the upstream areas without clear evidence of the difference that the water harvesting systems will make to their water supplies (see discussion in Swiderska et al. 2018).

Tunisian researchers have published various studies demonstrating cutting edge scientific tools and methods that are relevant to the quantitative assessment of effects of water harvesting on the water balance (Abdelli et al. 2017; 2016a; Adham et al. 2016b). The three aquifers in the Zeuss Koutine watershed are recharged through seepage through the river bed and infiltration into the landscape (Jarray et al. 2017). As there is little information on these processes, the recharge of the aquifers may be estimated based on the known natural recharge rates as a function of the rainfall. The best available estimate for the volume of rainwater recharge to groundwater achieved by the water harvesting structures was reported by Ouessar et al (2009), who observed that 22% of the 12-year average annual rainfall in the Koutine watershed (209mm) recharged groundwater, while 72% was taken up in evapotranspiration of crops, and the outflow was 6%.

A rapid estimation of the volume and value of recharge could therefore be as follows:

total annual volume of rainfall = 279,000,000 *0.209 = 58,311,000 m^3

total annual volume of recharge = 58,311,000 *0.22 = 12,828,420 m^3

total annual value of recharge if 1m^3 = 1Euro = €12,828,420

The Tunisian government has invested directly in increasing recharge to the aquifer through the construction and maintenance of artificial recharge structures in the upper part of the watershed (Hadded et al. 2013). Two years ago (2016-2017), three more recharge wells were constructed at Wadi Hjar to increase water recharge and two piezometers were installed to monitor ground water levels in the Grés de Trias aquifer with support from the European Commission through its Sustainable Water Integrated Management (SWIM) Programme project on

Water harvesting and Agricultural techniques in Dry lands: an Integrated and Sustainable model in MAghreb Regions (WADIS-MAR).

Data on water level fluctuations collected over the course of a year (September 2016 - September 2017) by pressure sensors in a data logger registered a 50 cm variation of the water level in the aquifer compared to a reference level, and a negative overall annual balance (Figure 2). The situation was more pronounced at one of the sites (mgarine), where the variation in the water level reached 70 cm and the annual balance was still negative. The total volume of extractions from the aquifer is not known.

(Figure 2: Registered water level variation in the Grés de Trias aquifer at Wadi Hjar)

Similar studies of groundwater recharge effects achievable using land and water management practices have not yet been pursued to the same degree at the other case study sites. There is therefore an opportunity for transfer of experiences both within the Arabian region, and beyond to the Sub-Saharan African case of ENNCA and others.

3.3 More water recycling: quality threats and energy demands for water treatment

In all four of the study areas, wastewater reuse is increasingly recognised as an alternative source of water with potential to boost overall water availability. This includes recycling of irrigation water by farmers who pump water out of the drainage areas in irrigated systems to reapply without treatment – as is commonly practiced in the Nile Delta and parts of the Bekaa (Table 5). It can also include reuse of treated wastewater where treatment plants are able to treat and supply such water to consumers and/or farmers. Reconfiguring the sequences of water uses can enable uses requiring water of higher quality (e.g. for drinking and other domestic needs) to be supplied first, before agricultural water uses that can have lower quality thresholds. However, transferring and treating water entails additional energy costs and emissions.

Table 5: Trade-offs associated with water treatment and recycling to cope with reduced downstream surface water availability

Adaptation	Service production $	Water security	Emissions reduction
Desalination (Koutine watershed)	↑	↓	↓
Planning water treatment systems (ENNCA)	↑	↑	↓
Reuse for irrigation with- and without treatment (Bekaa)	↑	↓	↓
Widespread reuse for irrigation often without treatment (Nile Delta)	↑	↑	↑

↑ positive effect

↓ negative effect

In ENNCA, and many other parts of Sub-Saharan Africa, there are relatively few water treatment facilities as yet. However, significant investments are anticipated over coming decades. This provides an opportunity to make well-informed choices and maximise the positive benefits and trade-offs by learning from what has worked elsewhere. Once again, energy choices can make a major difference to costs and emissions from water treatment technologies. They can also shape productive opportunities. Desalination technologies can remove more contaminants than conventional water treatment plants or environmental technologies such as slow-sand filtration units or constructed wetlands. However, they usually cost more and have higher energy requirements. Once again, solar-powered systems are a potential game-changer. But for the time being, these are not widely used in any of the study areas.

Lebanon's latest National Communications to the UNFCCC (MoE/UNDP/GEF 2016; MoE/UNDP/GEF 2017) focuses on increases in emissions associated with waste disposal and the treatment of wastewater. Water and air pollution render surface water resources unfit for use and so contribute to increasing demands for groundwater. A medium-term infrastructure investment plan (RoL 2018a) includes proposals for additional water treatment plants. The government's sectoral strategies on water and electricity also aim to increase the share of energy use that is provided from renewable sources of energy (RoL 2018b). In its National Communications to the UNFCCC (EEAA 2016), Egypt has also explored this opportunity and assessed the GHG emissions from wastewater handling for domestic wastewater, human sewage, industrial wastewater and the overall total from 1990 to 2005. Increasingly, such calculations may be taken into account in water management decision-making.

In Southern Tunisia, a new desalination plant to be constructed at Zarat in the Governorate of Gabes is expected to produce 50,000 m^3/d when it begins operating in 2021, increasing to 100,000 m^3/d by 2027 (36,525,000 m^3/yr)(desalination.biz 2018). The cost of the plant, together with three water storage tanks, and a pumping station has required the Tunisian government to commit €14.5 million to the project and to accept a loan from the KfW Development Bank of €82 million. To calculate the cost of production of a cubic metre of water from the desalination plant, in addition to the construction costs, it would be necessary to consider the recurrent costs e.g. for membrane replacement and others. It may also be affected by whether or not brackish groundwater is blended with seawater to increase the volume available for treatment. The source and cost of energy supply will be a major factor determining the cost of clean water production from the plant. If mains electricity is used, and this is mainly generated using natural gas imported from Algeria, then the cost of the water production will depend on this input.

In other parts of the Arab region, previous studies have identified a unit cost for desalinated water at around US$3.6/$m^3$ (ESCWA 2009) and a recent published study has compared the capacities and emissions rates of large desalination plants in California (Badiuzzaman et al. 2017). But these costs and emissions are context- and process-specific. In light of this, it is difficult to predict the emissions implications and the future costs of the desalination plant. Overall, the implications of different technologies are likely to change, depending on the volume of research and development attention they receive, as well as in response to commercial factors and economies of scale of production, competition, etc. It is not yet clear what difference could be made by policies intended to encourage the use of renewable technologies, such as solar energy. Little geoscientific work has yet been done to map the scale of the opportunities and priorities for investment in this area across the Arab region or beyond.

For smaller scale desalination units, solar power can be used (Salim 2012). In Egypt's desert areas, solar-powered stills have been demonstrated effective for desalination of small amounts of water primarily for domestic uses where other safe supplies are not available (Salem 2014). Where irrigated crops are sufficiently profitable, they can sometimes also justify the use of solar-panels to power reverse osmosis treatment systems that can treat sufficient volumes of water to irrigate high value crops (Ahmed et al. 2019). If they prove viable for pumping and treating shallow groundwater and drainage water, the use of solar-powered technologies that have been observed primarily in the desert reclamation areas could spread inward across the Nile Delta. This could transform individual farmers' income generation strategies, water management options and practices for coping with water scarcity and quality threats – just as the use of diesel-powered shallow wells recycling the drainage waters has been observed to have spread over recent decades (El-Agha et al. 2016; Molle et al. 2018).

4. Implications for decision-making and geoscientific research needs

As global interest in the extent and significance of trade-offs and synergies at the energy-water-environment nexus is increasing (IPCC 2018), geoscientific investigations generated by scientists from across the Arabian region and beyond can shed light on the stakes involved. Much more such scientific work may be required over the coming years. In each of the four cases that we have explored in this paper, geoscientific research is gradually building the robustness of the assessments of the energy and emissions implications of technologies to manage water, as well as the other costs and benefits. Collectively, the cases present a state of the art in available geoscientific assessment methods applied to quantify the stakes at the energy- water-environment nexus in some of the most water stressed and drought-prone basins.

The analyses and comparison between cases also highlight knowledge gaps and opportunities to boost and progressively enhance the information base for decision-making at this critical nexus. Countries are proceeding at different rates to develop emissions accounts and some other environmental accounting systems (e.g. energy accounting in Kenya (KNBS 2018) and other countries[4]. In this paper, a simplified illustrative approach was used to characterize the effects on economic productivity and demands for water and energy associated with each adaptation option that decision-makers could select. This can assist decision-makers to consider the relevant trade-offs and available information needed to evaluate and prioritize them. Where they may wish to obtain more detailed assessments, they can then commission the geoscientific research community to provide information to decision-makers, as needed.

[4] See: https://www.iea.org/Sankey/#?c=World&s=Balance

Some of the trade-offs and synergies including costs and implications for carbon emissions as well as water conservation are better understood than others. In the water-stressed regions of the world, many knowledge gaps remain and will not be filled until decision-makers commission the necessary studies to be done. Researchers can highlight the availability of relevant assessment methods to work toward filling these gaps in sustainability decision-making. Based on the review of the case study experiences, the remainder of this section discusses three common themes and concerns requiring geoscientific investigation at this critical nexus in the drought-prone regions.

4.1 Modelling approaches to quantify groundwater recharge as a low-emission nexus solution

The growing concern in many of the world's dry regions regarding increasing dependence on groundwater to meet domestic, irrigation and other water demands emerges strongly from all four case studies. On the other hand, careful management and use of groundwater can maximise the benefits from natural filtration, storage and distribution of water supplies in the subsurface. In regions that are prone to high temperatures, these are sustainable options. Conservation and use of groundwater can also help to avoid the construction and operating costs and emissions associated with man-made infrastructure for water treatment and transfers that require energy to pump water supplies from one area to another.

The cases that are explored in this paper provide insights demonstrating that geoscientific methods can be applied to assess the volumes of groundwater recharge and to test strategies to enhance recharge processes, as in the Tunisian case. This offers a useful example of an approach that could also be applied in other parts of the Arabian region, such as the Lebanese case, and also in Sub-Saharan Africa, as in the case from ENNCA. Mapping and characterising the processes affecting groundwater recharge and transport is also important in order to understand the vulnerability of water supplies that are stored in the ground. This can include vulnerability to contamination and increasing levels of salinity, which are critical concerns in areas where populations must depend on these sources for their drinking water supplies.

4.2 Integrating assessment of agricultural water and energy demands with other sectors

Across Africa, the extent of irrigated areas is expected to increase over the coming decades. The IEA (2017) predicts that by 2030 the combined additional electricity demand for water pumping, full mechanisation and post-processing will amount to 12 terawatt-hours (TWh), which is equal to a further 6% on top of the additional energy demands foreseen for increases in household access to energy. This review has identified examples of the application of geoscientific investigation to assess the emissions generated from different agricultural water management strategies. It has also explored available methods to compare these to previous studies of the energy implications of increasing groundwater use for irrigation in India.

The case study from Lebanon underlined the importance of balancing agricultural water uses with other demands across sectors at different times of the year. Insights emerging from this case study that could contribute to the nexus debate in other regions include the relevance of geoscientific techniques such as mapping of hotspots for observation of the uneven spatial and temporal distribution of peaks in energy demand. These tend to be concentrated during the drier seasons, and to exacerbate droughts. These inter-annual spatial and temporal variations should be captured in national energy and emissions accounts. They could be used to inform strategies for water and energy management at different times of the year during drought and non-drought periods.

4.3 Catchment scale water stress assessments to include demands of transitory populations

In the case studies from water stressed catchments that are explored in this paper, some relatively sophisticated modelling work has been done to assess water allocation planning for the settled populations. This includes studies carried out in the sub-Saharan African case (GoK 2012), as well as the cases from the Arabian region (as in Ouessar et al. 2009). In Southern Tunisia and also in Sub-Saharan Africa, assessments of water availability and demand are already providing a justification for large investments in desalination plants. The review of the future economic significance of water allocation decisions and their associated energy demands in the case from southern Tunisia suggests that some of these assessments and anticipated trade-offs may require further analysis.

The assessment of water needs for transitory as well as permanent populations that we observed in the Orontes case is very relevant elsewhere, including in the contexts of the Horn of Africa. In the ENNCA case study, the presence of a large refugee camp at Dadaab has caused periodic concerns about the additional environmental stress that can be created by addition demands for water supply and waste disposal. Water demands for temporary and seasonal residents and refugee communities are also relevant in Egypt. Seasonal fluctuations of population numbers and their implications for resource use can be high in many water scarce catchments – especially during drought periods. This has considerable implications for water and energy resource planning. It is an ongoing challenge also in various parts of Sub-Saharan Africa. Although it has not yet been possible to take the needs of the transitory populations into account, recent experiences from the Arabian region in coping with these water demands could offer instructive examples of how the geoscientific challenges involved in assessing water demands could be approached elsewhere.

5. Conclusions

Emerging options to make more use of low energy or renewable energy-powered technologies for water management offer opportunities for water managers across Africa and the Arabian region to reduce water stress and also maximise other positive trade-offs and synergies. These have implications both for short-term economic productivity and also for the longer-term effects of environmentally damaging emissions. Critical choices concerning investments in research and development of solar-powered technologies have particular implications for development in the driest and most water-stressed regions. In the four cases explored in this paper, geo-scientific investigations are contributing to the quantification of benefits and trade-offs for sustainable development. Common themes of interest for further geoscientific investigation identified concern recharge modelling, cross-sectoral energy and emissions accounting; and water and energy demand assessment for integrated catchment management planning.

The insights gained from geoscientific investigations and experiences presented in this paper from the selected case studies from the Arab region are of broader relevance also for decision-makers in other water stressed basins and regions. This is demonstrated in the case study from the Horn of Africa, and the wider discussion. There is an opportunity for decision-makers in the most water-stressed and drought-prone regions to improve their analyses of critical trade-offs by supporting further geoscientific investigation and exchanges on their priority questions. The implication for scientists in the Arabian region and beyond concerns the need to demonstrate the range of suitable geoscientific methods that are available and their relevance to addressing the challenges of drought and water stress. Decision-makers could then support their application to shed light on the trade-offs at the energy–water–environment nexus across the drought-prone regions.

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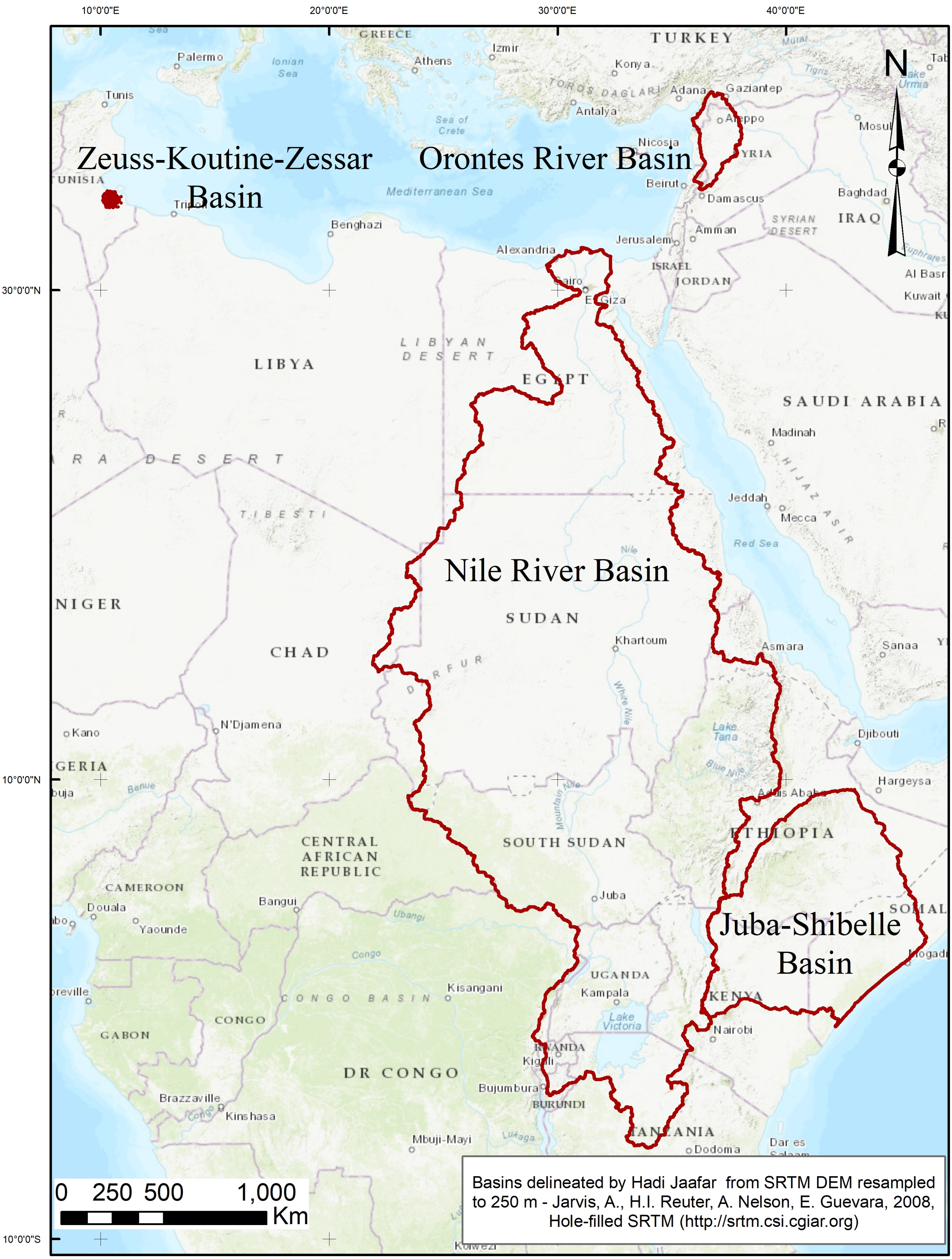
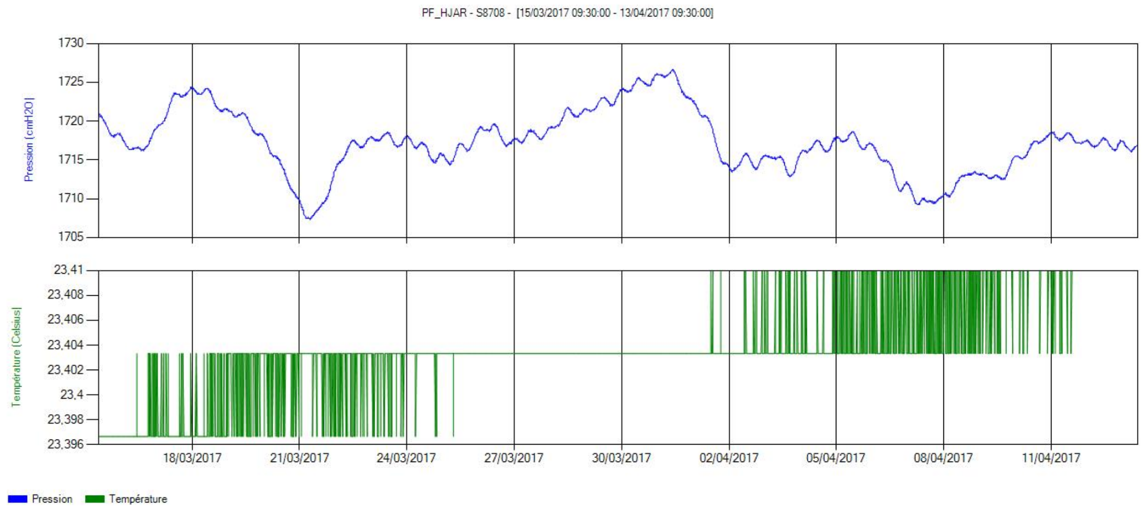

Zeuss-Koutine-Zessar Basin
Orontes River Basin
Nile River Basin
Juba-Shibelle Basin
N
10°0'0"E
20°0'0"E
30°0'0"E
40°0'0"E
30°0'0"N
10°0'0"N
10°0'0"S
0 250 500 1,000
Km
Basins delineated by Hadi Jaafar from SRTM DEM resampled to 250 m - Jarvis, A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled SRTM (http://srtm.csi.cgiar.org)
TURKEY
GREECE
LIBYA
EGYPT
SUDAN
SOUTH SUDAN
CHAD
NIGER
CENTRAL AFRICAN REPUBLIC
CAMEROON
CONGO
GABON
DR CONGO
UGANDA
KENYA
ETHIOPIA
SAUDI ARABIA
IRAQ
JORDAN
ISRAEL
RWANDA
BURUNDI
Mediterranean Sea
Red Sea
Cairo
Alexandria
Khartoum
Juba
Nairobi
Kampala
Addis Ababa
Asmara
Djibouti
Damascus
Beirut
Aleppo
Jerusalem
Amman
Baghdad
Jeddah
Mecca
Madinah
Tunis
Palermo
Athens
Benghazi
N'Djamena
Bangui
Kinshasa
Brazzaville
Kisangani
Bujumbura
Kigali
Dodoma
Lake Victoria
Lake Tana

Figure 2: Registered water level variation in the Grés de Trias aquifer at Wadi Hjar



Source: WADIS-MAR project