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# Cultivating the Desert: Irrigation Expansion and Groundwater Abstraction in Northern State, Sudan

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ABSTRACT: This study examines the socioeconomic features that underpin the expansion of groundwater-dependent irrigation in Northern State, Sudan. Groundwater development in the region serves as an economic lifeline given the poor Nile-based irrigation infrastructure and future changes in Nile hydrology. Groundwater-dependent irrigation is found to be expanding in previously uncultivated regions increasingly distant from the Nile. The study finds these historically marginal lands are targeted for capital-intensive agricultural projects because landholding patterns in traditionally cultivated areas preclude new large developments and improved infrastructure has lowered farming costs in distant terraces. Private companies and large landholders have a history of successful agricultural ventures in Northern State and are reliant on easily accessible and reliable groundwater resources for these new farms.

KEYWORDS: Groundwater abstraction, irrigation, agriculture, land tenure, Saharan Nile, Sudan

## INTRODUCTION

Northern State, Sudan is a critical agricultural province of 700,000 people in a nation of nearly 31 million that produces a disproportionate amount of staple crops (CBS, 2008). In average years, Northern State produces more than one-fifth of the nation's wheat, one-third of the beans and half of all dates (Abdalla, 2005). Northern State comprises a hyper-arid stretch of the Sahara and the northernmost reach of the Nile in Sudan. The majority of the state's agricultural production comes from low-lying basins, especially those close to the capital, Dongola. The fecundity of such areas is due to the effective conjunctive use of surface water from the Nile River and groundwater from both the Nile Valley Aquifer (NVA) and Nubian Sandstone Aquifer (NSA) that underlie the region.

Historically, farmers in Northern State relied on the Nile flood pulse to inundate basins which are extensive, flat areas separated from the Nile Valley stretching over 20 km from the riverbank in some places. The widespread flooding recharged the aquifers, which were used for supplemental irrigation. In Northern State, abstracting groundwater is the only viable irrigation alternative to surface water given the limited precipitation, on average about 20 mm per annum near Dongola (Vrbka and Thorweihe, 1993). In 1905, British officials oversaw the completion of the Seleim Basin canal system which conveys and stores Nile floodwaters in the basin and has underpinned the area's steady growth. Groundwater continued to be used alongside the large increase in surface irrigation to ensure the survival of both perennial crops and staples during low-flood years (Bacon, 1948). The introduction of suction pumps in the post-World War I period and then submersible pumps in the post-World War II period for increasingly deep groundwater pumping allowed intensification and extension of cultivation in Northern State (Wilson, 1991).

In the last two decades, irrigation in the Dongola area has moved east of the Seleim Basin, which is over 21,000 hectares (ha) and nearly entirely under cultivation (AHT, 1986; Hamad, 2005), into the Khway Basin[1] and even the open desert beyond the Nile alluvial regions. According to Bonifica's (1986) soil studies, the Seleim Basin and the area of the Khway Basin contiguous to it consist of 70,876 ha. The Khway Basin not contiguous to Seleim covers a further 71,926 ha. Irrigation in these newly cultivated lands of the Khway Basin and desert terraces relies entirely on groundwater, representing a fundamental shift from the traditional mode of agricultural production in Northern State. Historically, groundwater was primarily used either in morphological depressions for date plantations or as a buffer within basin areas for low-flood years, and was not the primary source of agricultural irrigation (Interviews, C).

This new groundwater-dependent irrigation has been made possible as much of Northern State is underlain by the Dongola Sub-Basin of the NSA, an immense groundwater resource with total estimated reserves of approximately 375,000 billion cubic metres (Bm$^3$) (UNDP, 2004), and an estimated storage of about 2100 Bm$^3$ in limited areas of Northern State alone (Kheir, 1986). Despite these reserves, significant drawdown of the groundwater table is possible, which already occurs in areas of intensive abstraction from the NSA, such as the Farafra Oasis in Egypt's Western Desert (e.g. Elsheikh, 2015); this is more generally a long-term risk because only very limited recharge from regional groundwater flowpaths and Nile infiltration occurs (Niestle, 1993).

The aim of this study is to examine the socioeconomic factors catalysing groundwater abstraction in Northern State in order to provide a multifaceted lens with which to view the general characteristics and sustainability of groundwater-irrigation expansion in the area. The purpose is to shed light on recent agricultural developments and the context from which they have emerged in a vital but understudied region of the Nile Basin. This study attempts to bridge political economy studies of irrigation and agricultural production in northern Sudan (e.g. Salman, 2010; Verhoeven, 2012; Keulertz, 2013; Woertz, 2013) and studies of Sudanese food production systems (e.g. Abdalla, 2005; Abdelrahman, 2012; Elnour and Elamin, 2014) to connect discussions of the physical resource and agricultural production systems to the socioeconomic and political context from which they emerge.

## CASE STUDY AND METHODOLOGY

### Hydrogeology of the Dongola region

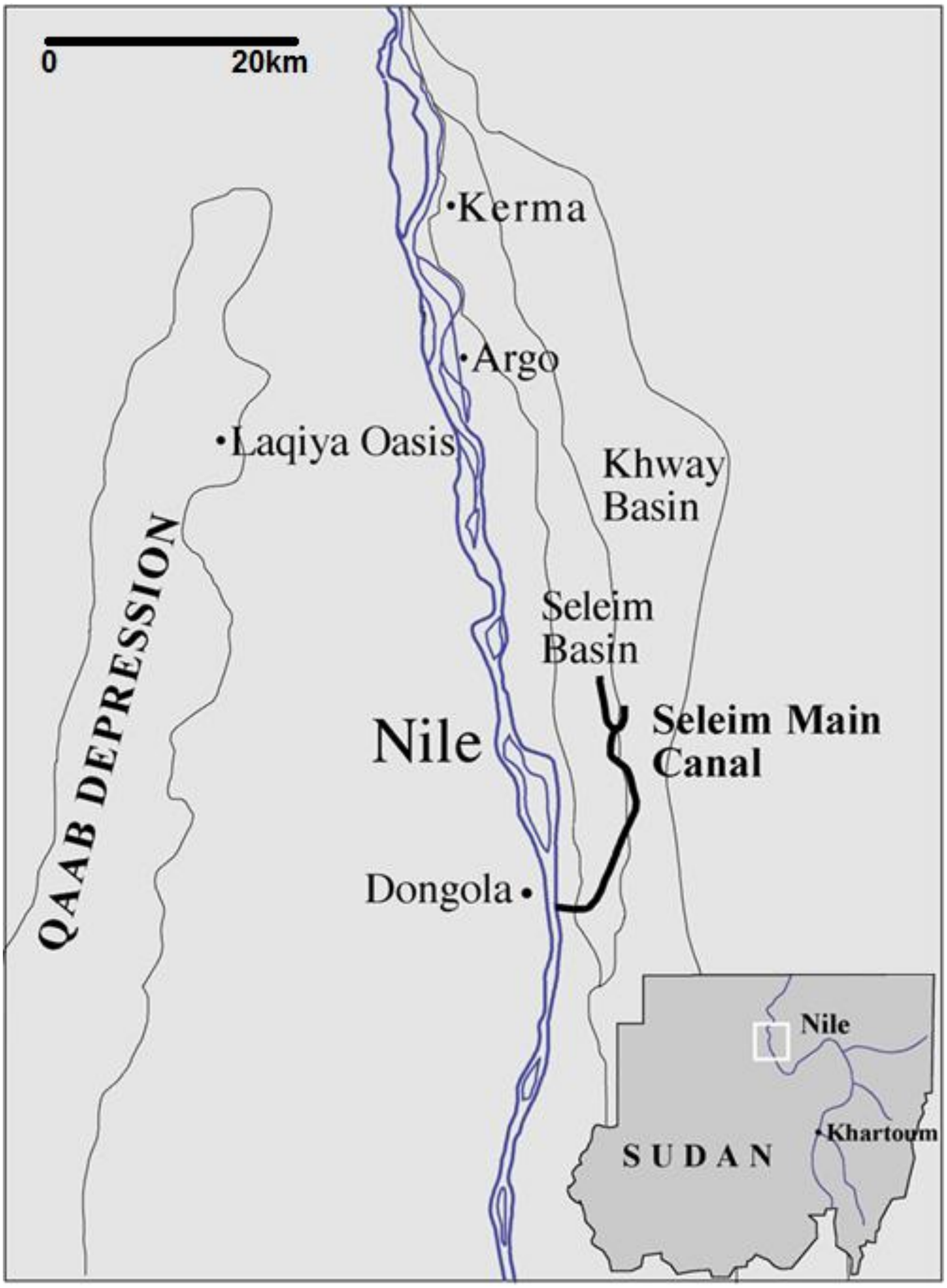
In the Dongola area (Figure 1), the NVA is a shallow, unconfined aquifer that extends in some places over 30 km from the Nile (Figure 2). The aquifer consists of Nile alluvial soils in which depth to groundwater is typically 2-5 m in areas adjacent to the river and within depressions, 3-10 m in basin areas including Seleim, 10-25 m in upper terraces including the Khway Basin and 20-40 m in the desert terraces wherever it is present (Abdo and Khalafall, 2000). Saturated thickness in the NVA varies significantly depending on seasonality and depth to the NSA formations but does not exceed 25 m from water-bearing depth (Kheir, 1986).

The NVA is separated from the NSA by a dark clay soil that increases in silt and gravel content with depth (Kheir, 1986). Most of the recharge to the NSA in the study area occurs along the interface of the aquifers with some regional inflow from the southeast (IAEA, 2007; Omer, 2011). Niestle (1993) estimated total recharge to both the NVA and NSA in the region as 180-190 million cubic metres (Mm$^3$)/year from the Nile, 70-80 Mm$^3$/year from recycling irrigation water and 66 Mm$^3$/year from regional inflow, while outflow west of the Nile is 1 Mm$^3$/year and riverbank storage, most of which

[1] Arabic names in this study are spelt phonetically as pronounced in the local dialect. Khway (خوي) in other publications and is spelled Khowi, just as Dongola دنقلا is at times spelled Donqulah.

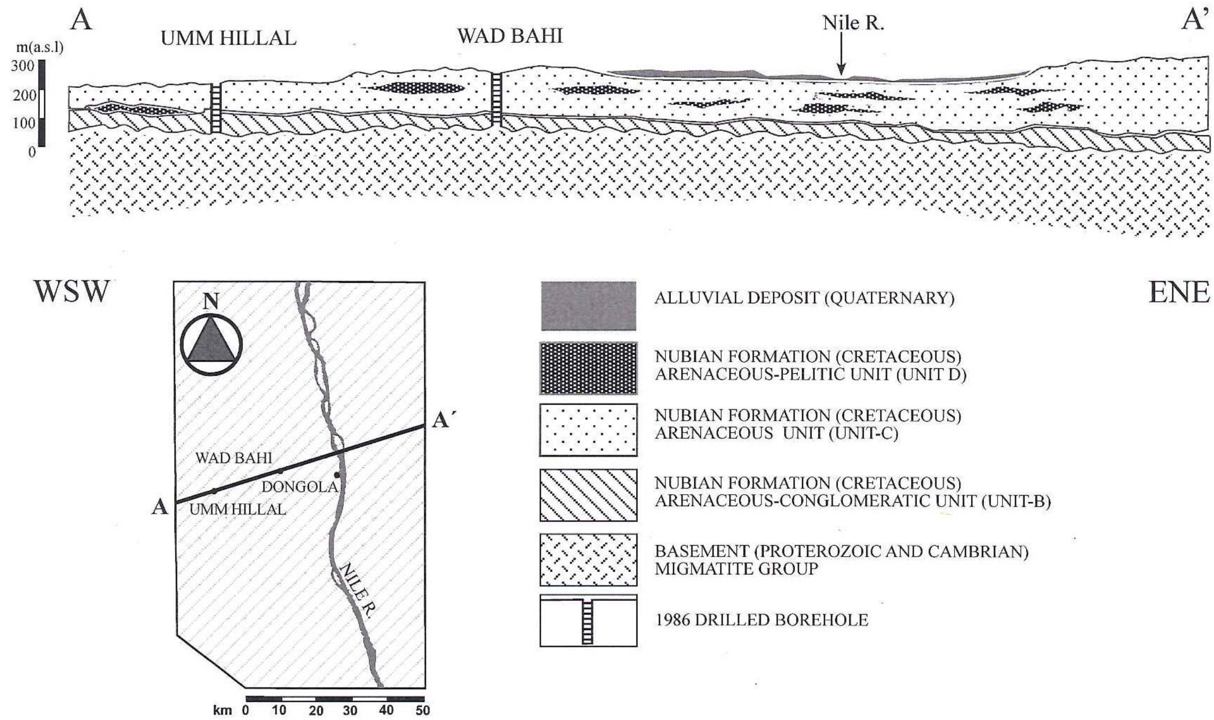
returns to the Nile after the flood peak, is 20-30 $Mm^3$/year. The NSA in the Dongola area has high variability in its vertical and lateral components leading to complex hydrogeological interactions with the NVA (Klitzsch and Squyres, 1990; Abdo and Khalafall, 2000).

Figure 1. Study area.




Source: Authors (Morphological areas, cities and the main Seleim Canal are outlined in a representative manner and are based on data from Lahmeyer (2006) and Google Earth).

Figure 2. Geological cross sections of the study area.




Source: Based on Bonifica, 1986.

Note: The NVA is contained within the alluvial deposits and the NSA within the various Nubian Formations until contact with the Basement Complex.

Nile water is markedly low in salts, and the local natural groundwater baseline in the NVA and NSA follow that trend. Typical conductivity values for the Nile before Lake Nasser are under 250 µS/cm, the NVA 200-500 µS/cm and regional NSA typically 500-1,000 µS/cm, indicating good quality for irrigation water from a salinity standpoint, although much higher values in the NSA can be reached naturally due to contact with the basement complex (Abdo and Khalafall, 2000). In intensively cultivated areas of the Nile Valley and Seleim Basin, salinisation of the soil and shallow NVA are increasingly important issues in localised areas because of the high evaporation rates associated with surface flooding irrigation – the predominant mode – and recycling of irrigation water. In some parts of the study area, soil and groundwater salinisation have caused abandonment of wells (Interviews, 8-9; C).

Extensive usage of NSA groundwater is a recent phenomenon, with the exception of the oases it supports such as Laqiya within the Qaab Depression, which have been exploited for millennia as archaeological remains attest (Newmann, 1993). Traditionally, farmers accessed groundwater in Northern State via hand- or animal-drawn shallow dug wells colloquially called *matara* (typically between 3 and 6 m in depth). Matara now have motorised pumps installed at the bottom of the vertical dug-shaft as well as uncased wells going deeper into the aquifer to access deeper groundwater than could be lifted by animal power. Depending on their location and total depth of the well, matara tap either the NVA or the NSA (Lloyd, 1990). As farmers utilise increasingly deeper wells, new boreholes or deepened matara, issues of long-term resource sustainability come into play because the NSA has very limited modern recharge and so overabstraction can lead to drawdown and cause upwelling of naturally saline groundwater (Abdo and Khalafall, 2000). Also, this recent phenomenon of groundwater-led irrigation expansion in Dongola introduces an additional element of potential future controversy in the allocation of Nile water resources as discussed in Section 5.2.

## Methodology

The study's primary objectives were to gather various perspectives about the main factors encouraging groundwater-dependent irrigation expansion in the Dongola region (Figure 1), with particular emphasis on the distant Nile alluvial and desert terraces which are previously uncultivated and do not have access to surface irrigation from the Nile. This is accomplished through two primary methods: analysis of national policy documents and statistics and interviews. In March and April of 2014 interviews were conducted with ten government officials and 12 academics in Khartoum and Dongola as well as 15 farmers and ten municipal water managers in the Dongola area. Interviews which are numbered were formal and structured and interviews which are alphabetised were informal and occurred as part of ongoing conversations with multiple individuals during fieldwork. Interviewees were guaranteed anonymity and the referencing herein attempts to ensure that while providing an indication of the individuals' seniority and role.

An interdisciplinary approach was taken to capture the socioeconomic and hydrological factors at play in such a dynamic system. More broadly, the integration of socioeconomic studies with hydrological information enhances the utility of each by illustrating the contextual milieu from which groundwater abstraction patterns emerge and also the impact that development may have on the agricultural production systems dependent on the usage of the water resource.

## THE DEVELOPMENT OF AGRICULTURE AND IRRIGATION IN NORTHERN STATE

### Sudanese agriculture and government policies

More than half of Sudan's GDP was reliant on agriculture and agro-processing before the beginning of Sudanese oil exports in 2000 (Ahmed, 2003). Despite a decline in its importance since then, its relative economic weight has increased once again since the separation with South Sudan reduced the government's oil revenues severely (FAO, 2011). Prior to partition in 2011, Sudan was estimated to have 82 million hectares (Mha) of land suitable for arable production, one-third of the nation's total area. The total land under irrigation is ~1,750,000 ha (FAO, 2011).[2] Although irrigated farms cover less than 10% of Sudan's cultivated area and produce under one-third of the nation's agricultural output by value, they produce the majority of export cash crops, including sugar and cotton, and import-replacement crops like wheat (FAO, 2011).

Improving agricultural yields and expanding the area under irrigated cultivation have been salient political goals for every regime since the Mahdist Revolution in the late 1800s (Gurdon, 1991). For this reason, as well as the 'developmentalist' ideology of post-colonial ruling regimes that favours large-scale, mechanised agriculture over traditional and largely rain-fed agricultural systems, the large majority of government funding and institutional support for agriculture has continued to flow to the irrigated sector (Adams, 1992).

Promoting wheat cultivation has been central to successive large-scale national development plans from the time of the Arab Breadbasket Strategy of the 1970s to the current Agricultural Renaissance Plan (Woertz, 2013). These grandiose strategies envision Sudan utilising its arable land with modern, capital-intensive agricultural techniques to decrease imports, increase foreign exchange and improve livelihoods. Urbanisation and changing dietary patterns have led to wheat imports ballooning from under 300,000 tons per year in 1980 to almost 2 million tons per year in 2008 when their value exceeded Sudan's total agricultural exports in value (Elgali and Mustafa, 2012).

[2] Unless otherwise noted this paper uses hectares, although it should be noted that Sudanese statistics are reported in feddans, where 1 feddan = 0.42 ha.

Government incentives linked to these development plans have at times narrowed the wheat production-consumption gap considerably. In the early 1990s, bread subsidies were removed and wheat-growing subsidies increased leading to nearly 90% wheat self-sufficiency (Abdelrahman, 1998). However, these policies faltered in the early 2000s when the lack of financing and difficulty sourcing agricultural inputs such as fertilisers and insecticides resulted in a collapse of cultivation of the wheat area (Abdelrahman, 2012).

Because Northern State is an area identified within the Agricultural Renaissance Plan for expansion of major wheat cultivation, national agricultural policies focus on and have the greatest direct intervention in wheat production systems (ARP, 2008; Interviews, 5-6, C).

## Irrigated agriculture in Northern State

The three crop seasons in Northern State are the winter, summer and flood seasons. The winter season is by far the most important, the summer is usually when lands are left fallow due to adverse climatic conditions, and flood season cultivation is limited to areas that directly receive the Nile flood (El-Houri, 2007).

Since the beginning of the 20th century, irrigated agriculture in Northern State has relied primarily on flood-basin irrigation with both river and groundwater pumping playing increasingly important roles over time (Allan and Smith, 1948). The 1938 flood was high and 28,500 ha were cultivated in Dongola whereas the 1941 flood was low and under 2000 ha were cultivated (Tracey and Hewison, 1948). Currently, the Nile flood level is still the largest factor determining annual agricultural production in Dongola though reliance on the flood pulse has lessened due primarily to groundwater pumping as well as, to a much lesser extent, pumping from the river (Lahmeyer, 2006; Interviews, C, D).

Within this system, the most low-lying areas that were inundated nearly every year were quickly fully farmed. However, the Nile's flood level is notoriously irregular and also extant canal systems have deteriorated over time and only serve small portions of the Seleim Basin and nearly none of the Khway Basin (Lahmeyer, 2006; Interviews, A, C, D). As a result, expansion of cultivation even in flood basins beyond the area effectively served by canals has relied on extensive groundwater usage. In Seleim, thousands of matara were in use by the mid-1980s (Kheir, 1986), and beyond the limits of the Nile flood and canal systems, groundwater has been the sole agent of agricultural expansion (Interviews, C, D).

## History of groundwater usage in Northern State

Macalister et al. (2012) estimate that only 60,000 ha of Sudan's irrigated area are supplied solely from groundwater out of a potential of 1.4 Mha. Much of this potential groundwater irrigation area exists within Northern State in desert and wadi terraces underlain by the NSA (Ibid). Adelana and MacDonald (2008) state that the lack of historical usage of groundwater and education in agricultural practices are two of the primary barriers to the expansion of groundwater-based irrigation in sub-Saharan Africa generally, as is the paucity of competent well-digging organisations and firms. Dongola, in contrast, has all of these features in abundance (Interviews, C-D). The long-term history of successful groundwater irrigation and relatively high socioeconomic status of Northern State's population are therefore highly relevant factors which facilitate and encourage modern groundwater-based irrigation.

Since the early 1900s, private landholders of the Northern State have been the predominant users of groundwater for irrigation in Sudan. Northern Province – the colonial precursor of Northern State, which also included the cities of Atbara and Shendi – had over 90% of registered agricultural groundwater wells in all of Sudan in 1943 (Allan and Smith, 1948). By 1945, there were nearly 200 motorised river and groundwater pump schemes in Northern Province, of which over 150 were private schemes (ibid). Tracey and Hewison (1948) singled out Dongola farmers as having the best-run pump schemes in Northern Province with well-established institutional operations, keeping of accounts, and knowledgeable farmers.

This success continued in the post-independence era. During agrarian reforms of the 1970s, the government nationalised failed private pump schemes. Of hundreds, only one was in Northern State (Davies, 1991). In 1979, over 80% of all land in privately run river and groundwater pump schemes, ~87,000 ha, were in Northern State. This is notable because at a time when most agriculture programmes were government-run, the private sector dominated Northern State agriculture and was economically successful (Davies, 1991). Northern State today follows only Khartoum and Gezira States in the UNDP's (2012) human development and economic index for Sudan, illustrating the State's continuity of relative prosperity, and the adult literacy rate of over 70% is among the highest in Sudan.

## Landownership and groundwater abstraction in Northern State

In Northern State landownership and tenure fall into three categories: 1) free-holding *milik* land is privately owned, mostly by smallholders, and limited in area to the land registered by owners in 1905 in the Nile Valley, near towns and in low-lying basin areas. Irrigation on milik lands has expanded substantially over time in tandem with increased usage of river and groundwater pumps and still constitutes the majority of irrigated land; 2) *miryi* lands are those adjacent to milik holdings. They are technically government holdings but are leased for long durations under varying statutory and regulatory arrangements. The average size of such leased holdings is ~4.2 ha; 3) government lands in upper terraces. These typically offer much larger holdings than miryi lands and are predominantly government irrigation extension schemes and company-leased farms (Abdalla, 2005).

In the Dongola area, 54% of cultivated area is on milik, 31% of cultivated land is rented, mostly miryi lands in basin areas often more distant from the river, and 15% is government-owned (El-Houri, 2007). Abdalla (2005) reported that in Dongola, approximately 55% of agricultural land is irrigated solely from groundwater and about 9% uses both groundwater and Nile surface water in a given season.

There are four types of pump schemes in Northern State: private, company, cooperative and extension. Pumps of private schemes are typically 3-4 inches in diameter and are owned individually or within a family and predominantly occupy milik and miryi lands. The 15,000+ private pumps in the Dongola area make up over 95% of all pump schemes, and approximately 11,000 of them, the vast majority of which are matara, utilise groundwater (Abdalla, 2005). While matara make up the majority of pump schemes, they irrigate only 64% of the total cultivated area.

Company schemes occupy miryi and government lands, are all over 200 ha and use large-bore pumps of 10-inch diameter or larger. As of 2002, 39 company schemes in Dongola cultivated over 64,000 ha and devoted twice as much cultivated area to wheat and significantly greater areas to alfalfa relative to other schemes, indicating their focus on national and export markets (El-Houri, 2007).

Privately initiated and run cooperative schemes mostly occupy milik or miryi lands and are groups of individual landowners who pool resources for canal or pump maintenance, fuel costs, tractor usage, etc. Cooperative schemes are led by a board of directors responsible for the timing and distribution of irrigation water according to the group's covenant. As of 2002, 46 cooperatives farmed ~12,500 ha (Abdalla, 2005).

Expansion schemes are government-funded, relatively large-scale irrigation developments. Since 2001 they have been privately operated by Sudanese companies or tenant farmers supervised and subsidised by the government through infrastructural maintenance and at times agricultural input subsidies. They were created as part of the National Wheat Programme and other government programmes prior to the mid-2000s to expand irrigated area or to consolidate smallholders to create economies of scale, and in this study area are exclusively on government lands in Khway (El-Houri, 2007; Interviews, C-D).

The expansion of cultivation beyond areas which typically receive the flood began in the early 1990s and is primarily a response to the complete utilisation of more easily cultivated areas (Hamad, 2005). However, growth patterns are shaped by landholding structures and the entities involved in new developments. The process by which land leases occur is opaque, and official investment statistics were not made available during the course of the study. Interviews (C-D), though, suggested that new farmland development in relatively remote sections of Khway and desert terraces is fuelled by absentee Sudanese landholders and companies and, to a lesser extent, Egyptian and Qatari investment firms. Private smallholders and leasers, in contrast, have continued to expand cultivated area within the Khway Basin in a sequential and contiguous fashion.

During fieldwork all farms surveyed inside the command area of the Seleim Basin used surface flooding to irrigate crops through ditch and furrow systems connected to the Nile canal system, a groundwater well with screens less than 10 m deep, or both. In the southern and western areas of Khway, surface flooding was used with diesel-powered pumps in matara or groundwater boreholes which are between 60 and 100 m deep. In the northern and eastern parts of Khway and the desert terraces, company and government farms used electric-powered centre-pivot irrigation systems connected to boreholes with depth to screen between 100 and 210 m. These farms included one expansion scheme that was at least 10 years old and company farms all less than 5 years old that were owned by Sudanese and Egyptian agribusinesses (Fragaszy, 2014; Interviews, 6, C-D).

## SOCIO-POLITICAL DRIVERS OF GROUNDWATER IRRIGATION IN DONGOLA

In light of the above agricultural background, a review of national policy provides the basic framework to examine political drivers of groundwater-based irrigation in Northern State. From 1999, the Sudan National Water Policy (Ministry of Water Resources and Electricity, 1999; hereafter SNWP, 1999) outlines the principles on which municipal and irrigation water supply legislation rests. From 2008, the Agricultural Renaissance Plan (Government of Sudan, 2008; hereafter ARP, 2008) is the current agricultural development policy for Sudan. From 2001, the somewhat dated Report of the Water Resources Group on Groundwater Development for Agriculture (Ministry of Water Resources and Electricity, 2001, hereafter GWG, 2001) has been the guiding document for groundwater development for agriculture (Interviews, 2, 5, 7, A).

### The National Water Policy

The SNWP (1999) and associated official documents published by the Ministry of Water Resources and Electricity (e.g. Abdalla and Mohamad, 2007) indicate that for the time being, government-backed development of the NSA will be limited to municipal water supply due to the high cost of development and, in most areas, its remoteness from population centres. Aside from low levels of investment that preclude groundwater development for agriculture, the Ministry of Water Resources and Electricity currently focuses resources on the priorities of the Dam Implementation Unit which primarily emphasises hydropower production rather than groundwater and river-based irrigation schemes in Northern State (SNWP, 1999; Interviews, 1, 3, 5).

The SNWP acknowledges that, over time, state governments are expected to exert stronger pressure to develop their own groundwater resources. Currently, this is not a persistent feature of Northern State development projects because of cost and reliability considerations (Interviews, 2-3, A). The language of the SNWP related to irrigation water supply revolves around surface water; there is no specific differentiation between groundwater and surface water in terms of management, consumption or pricing, with the underlying assumption that legislation will centre on the Nile and other surface water schemes.

The history of government-sponsored development plans leading to exhaustion of groundwater resources is a dissuading factor for modern government initiatives. During the droughts of the 1980s, government-funded groundwater irrigation schemes led to over-abstraction and misuse of grazing lands, which contributed significantly to humanitarian crises, especially in Darfur (Interviews, 8-9).

Northern State officials from the Ministry of Water Resources and Electricity and the Groundwater and Wadis Directorate as well as the Ministry of Agriculture emphasised that current expansion of groundwater abstraction is occurring under private auspices. While one directive of the Ministry under the SNWP is to facilitate such private-sector development and it monitors as well as provides information and technical support to farmers and companies drilling wells, it does not currently offer major direct support in the form of subsidising well-drilling or pumping equipment as it has done in the past. Rather, to the extent that State officials base decision-making on national policy when implementing plans, they utilise the SNWP primarily as the policy rationale for maintaining and improving surface irrigation systems as well as expanding groundwater abstraction for municipalities (Interviews 4, 6-7, A, C).

### The Agricultural Renaissance Plan

The Executive Programme of the Agricultural Renaissance Plan (ARP) (2008) is the official Sudanese agricultural development policy, though its replacement is currently under development (Interviews, 5-8). In terms of content and goals it is similar to past developmental programmes and reflects the long-term logic of agricultural policy in Sudan (Verhoeven, 2012). Overall, Sudanese officials and academics characterised the ARP's agricultural output targets as the product of bureaucrats who are not restricted by political and financial realities, and they said its emphasis on improving the enabling infrastructure and market factors pertinent to agricultural production have been more successful than direct interventions in agricultural production systems in Northern State explored further in Section 4.6 (Interviews, A-C).

The ARP does not directly emphasise expanding groundwater-based irrigation. However, it adopts several elements of the previous National Wheat Program, an agricultural development strategy promulgated in the late 1990s that had the stated goal of meeting domestic consumption by 2011 (ARP, 2008). It would accomplish this by increasing average yields by nearly 50% and expanding nationwide irrigated wheat areas from ~281,400 to 672,000 ha – of which approximately 113,400 ha would be in Northern State and implicitly lead to increased groundwater abstraction – through direct agricultural subsidies, technology transfer, and infrastructural improvements including maintenance and expansion of irrigation canals (Elamin, 2004).

General infrastructural improvement, not infrastructure specifically linked to irrigation, is the main success story of the ARP and the most relevant avenue through which it has impacted groundwater abstraction in Dongola. Rural electrification made possible by the completion of the Merowe Dam in 2009 and the construction of a bridge linking Dongola to Seleim and improved highways between Dongola, Khartoum, Merowe and by extension Port Sudan have had major impacts on farmers in the Dongola Region explored further in Section 4.5 (Interviews, 8-9; B-D). At present, though, Sudanese dams cannot function effectively as both irrigation reservoirs and hydropower installations due to siltation issues (Whittington et al., 2014). Therefore, the competing claims of energy generation and irrigation expansion come to a head. So far, integrated nexus development has been limited because financial limitations preclude development of both, and the overriding emphasis to date has been on hydropower production from dam operations in Northern State (Keulertz and Woertz, 2015).

In general, the ARP is designed to empower the private sector by improving market conditions for Sudanese farmers rather than through direct government control, though cultivation targets were set for each state. Volatility of food prices in 2008-2012 constrains the possibility of examining the impact of ARP policies alone on wheat expansion in Northern State (World Bank, 2012), but statistics of the Ministry of Agriculture show that from 2003 to 2013 the area of wheat cultivation has buoyed drastically and ranged from less than 25,000 to more than 125,000 ha per year (Table 1). It never met ARP targets and peaked during the beginning of the programme in 2008/9 – coinciding with the highest international spot market prices for wheat.

Table 1. Wheat cultivation statistics for the Dongola Region (in feddans).

| | Northern State (total) | | Dongola area | |
|---|---|---|---|---|
| | Cultivated | Target | Cultivated | Wheat (% of cultivated area) |
| 2003/04# | 129,128 | | 77,274 | 40 |
| 2004/05# | 315,000 | | 86,200 | 41 |
| 2005/06# | 152,693 | | 103,591 | 49 |
| 2006/07# | 310,785 | | 135,840 | 54 |
| 2007/08# | 156,257 | 185,061 | 51,966 | 57 |
| 2008/09# | 300,000 | N/A | 116,000 | 81 |
| 2009/10 | N/A | N/A | N/A | N/A |
| 2010/11* | 75,814 | 123,572 | 29,308 | 43 |
| 2011/12* | 70,086 | 120,000 | 28,911 | 48 |
| 2012/13* | 63,606 | 120,000 | 23,058 | 39 |
| 2013/14* | 65,368 | N/A | 22,290 | 38 |

Source: Northern State Ministry of Agriculture Statistics (2003-2014).

* Indicates winter crop area only, # indicates the entire Dongola Region.

The volatility of wheat cultivation and the failure to meet wheat production targets reflect the general long-term trend in Sudan in which government policies, financing and incentives lead to rapid increases in wheat cultivation that fall just as quickly once price subsidies and other measures are reduced (Elgali and Mustafa, 2012). Indeed, farmers in Khway reported that many state-funded extension farms created to expand wheat cultivation either through the National Wheat Program or the ARP began to grow alfalfa for export once oversight became lax and price supports disappeared (Interview, D).

### The Groundwater Development for Agriculture Strategy

The GWG (2001) is the national policy document that formed the Groundwater and Wadis Directorate, outlined baseline features of groundwater resources available for agriculture in Sudanese states, and issued the guiding principles of groundwater development for agriculture in Sudan. The GWG prioritises regions most apt for groundwater-based irrigation development without specifying development targets. According to the GWG, Seleim and Khway have the greatest potential for groundwater-based irrigation expansion in Northern State and within the greater Dongola Sub-basin a further 125,000+ hectares are deemed irrigable in the depressions, wadi courses, and Nile basin (GWG, 2001).

However, the GWG does specify funding mechanisms and indeed is more notable for what it replaces than what it proposes. It was promulgated after the failure of the highly ambitious and unrealistic 1992-2002 groundwater development plan which envisaged national groundwater abstraction for irrigation increasing to 3.2 $Bm^3$/year by 2010, a nearly fourfold increase from the 870 $Mm^3$/year cited for 1992 values (GWG 2001).

The 1992-2002 groundwater plan included specific projects, a development timeline and dedicated funding from the central government. A large number of groundwater wells were constructed through the programme. However, within three years of its launch, government subsidies for well-drilling, maintenance and operations decreased significantly leading to a nationwide collapse of the programme. Some state governments and foreign aid or development agencies replaced central government funding and continued to expand municipal supplies drawn from groundwater, but the large majority of irrigation boreholes dug through this initiative went unused (Interviews, A; GWG, 2001). For example, 50 large-diameter irrigation boreholes were dug to support food security initiatives in Omdurman. But because the state agricultural bank was unable to finance the creation of new farms, the wells were not utilised (GWG, 2001).

The 1992-2002 development plan failed because of institutional dysfunction as much as financial problems. Its failure, in combination with the failure of government-funded groundwater development initiatives such as those related in Section 4.1, continue to influence official thinking on groundwater development; they are a primary reason why the central government currently does not get highly involved in groundwater irrigation development and instead seeks to guide private investment into targeted areas, and otherwise delegates primary responsibility for groundwater development for irrigation to state governments (Interviews, 1, 2, 5-6, A).

**Surface irrigation and Nile flows**

One element of government policy that severely impacts groundwater development is investment, or lack thereof, in surface irrigation infrastructure. Farmers unanimously prefer irrigating with Nile water to groundwater, provided that surface water delivery is guaranteed (Abdalla, 2005; Interview, C). Irrigation costs absorb 25-35% of Northern State farmers' overhead, the single largest expense (Abayazeed, 1999). Farms using surface irrigation face significantly lower total irrigation costs – nearly 33% less for private farmers and about 10% less for companies – than groundwater irrigators. Also, the Nile's silt content means that surface irrigators spend approximately 10% less on fertiliser than groundwater irrigators (Abayazeed, 1999).

The lack of significant canal and pump system expansion in the last decade is a major driver of newly built farms being groundwater-dependent despite negative economic incentives. In the study area as of 2006, approximately 15,000 ha were included in Nile pump-powered canal irrigation schemes, of which under 9000 has were cultivated (Lahymeyer, 2006). Since then, several large pumps have been added to ensure predictable volumes fill the canals each flood season and in some cases to provide supplemental irrigation water in the winter growing season. But these primarily serve existing canal systems, such as Seleim's command area of 4200 ha, rather than new regions. The expanded canal in Argo serves the upper Seleim Basin but is a flood conveyer canal which, except for a small area (<1000 ha), is not served by pumps. The Korti irrigation district, completed in 2009 and located southeast of the study area was the last new, major surface-water diversion scheme (UNEP, 2013).

Northern State and Khartoum officials said that no other major public or private surface irrigation works were under consideration and the priority is maintaining and improving the performance of existing basin canal irrigation systems (Interviews, 2, 4-6, A). Therefore, recent surface irrigation improvements have increased the area prepared to use Nile waters, and rehabilitation of existing schemes has increased the area actually utilised within existing schemes, but the expansion is incremental (Interviews, C, D).

The German conglomerate Lahmeyer International designed a series of canal systems to utilise water from the Merowe Dam Reservoir and downstream pump stations to irrigate 140,000-500,000 ha between Merowe and Dongola depending on the specific construction option chosen (Lahmeyer, 2006). However, government officials said it is highly unlikely that major components will be implemented in the near future because the costs are prohibitive and the government is focused on rehabilitating and improving extant irrigation districts (Interviews, 2, 5). Officials added that Sudan approaching complete usage of its Nile allocation was not an impediment to the project and was a factor considered during the planning process (Interviews, 1-3, B).

Such major expansion of river-fed irrigation in the Dongola area would necessarily require significant Nile abstraction. A rough and absolute minimum estimate of water requirements for 150,000 ha of wheat grown in the area indicates that 365 $Mm^3$/year would be needed, assuming all crops are grown using centre-pivot systems, two crop cycles per year and 11 irrigation applications per crop. The steps to arrive at this figure, about 2% of Sudan's annual allocation according to the 1959 Nile Waters Treaty, are shown below.[3]

To give an example of farmers' preferences for Nile water over groundwater, interviewees related the impacts of improved canal pump infrastructure in the Seleim Basin near Dongola and Argo (Interviews, B-D). Immediately following the completion of the pumping stations noted above, farmers in the benefiting areas shifted from groundwater to Nile irrigation. Within ten years, farmers in some areas of Seleim changed from worrying about the drawdown of the groundwater table to soil saturation because of rises in the groundwater table resulting from surface irrigation increases and reduction in groundwater abstraction. In Argo, the groundwater table rose so high that it caused local brick buildings to collapse.

In summation, the Northern State government prioritises refurbishment and installation of pumps for existing canal systems over the creation of new irrigation districts. This preference stems from a desire to mitigate declining performance of existing basin production systems and to prepare for the expected drastic changes in the Blue Nile's hydrological cycle resulting from the completion of a cascade of upstream dams (Interviews, 2, 5-9). Interviewees stated that the operation of the Merowe Dam[4] has reduced flood peaks in Dongola slightly, but the authors did not find corroborating evidence and modelling such impacts was beyond the scope of this study (Interviews, D).

The completion of the Grand Ethiopian Renaissance Dam (GERD) will almost certainly reduce the Nile flood peak during its period of reservoir filling and beyond, but any discussion of the specifics is only conjecture at this time, since the dam's operation rules have not been made public (Interview, 2). While further information may become available after the publication of the GERD's recently initiated environmental impact assessment (phys.org, 2015), what is clear is that under current conditions and with extant infrastructure, any major reduction in the Nile flood pulse would result in severely reduced cultivated area in Northern State and increased pressure on groundwater systems.

## Socioeconomic drivers of groundwater irrigation expansion

The 2009 completion of the Merowe Dam power station resulted in Northern State consumer electricity prices falling by approximately 50%. Also, power outages occur far less frequently than before and now rarely last longer than a day whereas earlier they frequently lasted for days at a time which often had disastrous impacts on farms reliant on electricity that did not have independent generators. Increased availability, affordability and reliability of electricity is a prime factor enabling wide-scale and intensive groundwater-dependent irrigation development in Dongola (Interviews, C-D).

A 2003 study found that in Northern State, electric pumps' running costs on average were 58% less than diesel pumps for water lift of 10 metres – the average depth of wells in the state. Smaller though still significant savings accrued for deeper boreholes (Ahmed, 2003). In 2006, diesel subsidies for agricultural pumps were phased out in Northern State due to government financial constraints and a

[3] Lahmeyer (2006) recommends using 7-span centre-pivot rigs which cover 66 ha each and apply 97 litres of water per second over 21 hours per irrigation application for a total of 7.3 million litres per day per 66 ha. Faki et al. (1998) indicate that wheat growing seasons in Northern Sudan are approximately 90-100 days with typical irrigation applications between 10 and 15 days apart. Fadul and Mustafa (2004) showed that irrigations every 7 days are preferable. This basic calculation assumes 11 irrigations per crop season and 16.6 $Mm^3$/day per irrigation application. Any increase in irrigation system throughflow, number of applications or the utilization of flooding irrigation – much is far more common in Northern State than centre-pivot – would greatly increase water requirements.

[4] The Merowe Dam, approximately 300 km upstream from Dongola, has generated over 55% of Sudan's total electricity supply since 2010, has a reservoir capacity of approximately 12 $Bm^3$ and permanently flooded 5500 ha of irrigated farmland and 1100 ha of flood recession farmland (Sudanese Company for Electricity Distribution Ltd., 2013; Teodoru et al., 2006).

desire to liberalise the agriculture sector, further incentivising farmers to utilise electric pumps (Interviews, C).

Although the cost to purchase, operate and maintain an electric pump is about 1/3 of diesel pumps, still the majority of pumps sold in the state are diesel-powered. This seemingly contradictory point is due to the fact that connecting an agricultural pump to the electric grid costs a one-off fee of around USD 1,500,[5] over half the average annual per capita income in Northern State according to purchasing power parity (UNDP, 2012). As a single payment, and even with the option to pay the utility over three years, this sum is prohibitive for the tenant farmers and smallholders who dominate the Nile Valley and the Seleim Basin (Interviews, C-D).

This can be explained by two attitudes: 1) farmers do not want to buy electric pumps because they are locked-in with diesel pumps and already have sunk costs; 2) tenant farmers and smallholders are unable or risk-averse to taking loans to pay for electrification. Financing is available through the state agricultural bank, but collateral requirements put loans out of reach of most tenant farmers and for smallholders they typically approach a farmer's entire holding. Interest is typically over 10% per annum and failure to repay the loan would result in the farmer losing his/her land. Combined with a general distrust of government agencies such as the agricultural bank, farmers are hesitant to risk their livelihoods to take substantial loans to help them reduce long-term costs but not fundamentally alter agricultural practices (Interviews, A, C-D).

Therefore, the drop in electricity prices is especially relevant for large operations and contributes substantially to the expansion of groundwater-dependent irrigation in the distant terraces by making the cultivation of those regions more economically viable. During the course of the fieldwork, all but two farms surveyed in the Khway Basin and desert terraces were farms started since the completion of the Merowe Dam that used electric pumps (Interview, D).

Issues of landownership and tenure discussed in Section 3.4 are also primary reasons why these newer, larger schemes are located farther from the river and in desert terraces. In Sudanese culture, ownership of land continues to be a source of prestige, and the sale of inheritable and privately owned family land outside the immediate family is rare because of inheritance law and traditions (Tothill, 1948; Interviews, C). Therefore, competition for prime land in the Nile Valley and the lowest parts of the basins which are dominated by milik holdings drives up land prices significantly (Wohlmuth, 1991). In contrast, since the Khway Basin and desert terraces are largely empty desert areas that are miryi or government lands, it is easy to agglomerate larger holdings necessary for centre-pivot and mechanised agriculture.

Distant alluvial terraces and desert soils are also frequently affected by salinity in the top layers. Local academics stated that recent research has focused on flushing salts from these layers using groundwater. They reported – though corroborating information was not provided or obtained to describe the processes or specific results – that yields of salt-tolerant crop varieties increased after flushing salts through irrigation and crop growth. Following this procedure, productive crop varieties can be grown profitably within five years (Interviews, 6-8, C). The ability to weather low returns or even losses on large farms until salts can be flushed from the topsoil further limits these marginal areas to large-scale, capital-intensive developments.

Lastly, whereas conflicts between settled farmers and pastoralists are common in other states, this feature is largely absent near Dongola since there are only ~14,000 traditional nomadic herders in Northern State, much fewer than in other states, and their population has been declining steadily in

[5] SDG9000, USD approximation with the exchange rate of 1SDG = ~USD0.15 in March 2014.

recent years (CBS, 2008).[6] Many of these nomads in Northern State are involved in large-scale cross-border camel herding that brings livestock from southern Sudan to Wadi Halfa and then on to Egypt. These are well-established trade routes which, to a large extent, have not been threatened or blocked by farm developments so far (Interviews, C-D).

### Patterns of agricultural expansion

Agricultural development patterns in Khway exemplify these socioeconomic drivers of groundwater abstraction (Interviews, 8, C-D). Parts of southern Khway visited during fieldwork are intensively farmed, primarily by smallholders who use matara. Some isolated areas have experienced significant soil salinisation and water table drawdown as a result of poor practices; several capped wells were passed with salt crusting visible on the adjacent ground surface and one matara near a capped well produced water with conductivity values over 2,300 µS/cm (Fragaszy, 2014). Other highly fertile sections of southern Khway are left barren because the landowners are unable to finance cultivation and are unwilling to sell their milik land or give up their miryi leases. In comparison, northern Khway has much larger uncultivated expanses that are getting leased for large-scale, capital-intensive farms that grow wheat and alfalfa and that are built near access roads to the new highways (Interviews, C).

According to interviewees (8-9; C-D), investors in the Dongola area first target Khway, then the desert east of Khway close to the highways, and finally desert terraces west of the Nile because the soils on the west bank are poorer. West of the Nile in the Laqiya and Kerma areas there are recently developed centre-pivot operations owned by Gulf investors which generally show similar development patterns to those in the eastern desert terraces but smaller in scale (Interviews, 7; A, C).

Cultivation of date palms has also expanded significantly in the morphological depressions like Qaab leading to groundwater table drawdowns. A farmer interviewed there noted that his well, which was previously artesian, now has a static water level 3.5 m below the ground, and he blamed water level drops on the recent expansion of a nearby date plantation which utilised several motorised pumps (Interviews, A, D; Fragaszy, 2014).

### Groundwater usage

Determining whether groundwater abstraction has increased absolutely in the study area in recent years is not possible due to the paucity of official statistics. The values shown in Table 2 are the only groundwater abstraction statistics available, and while obsolete by virtue of their age, they are still useful to characterize groundwater users and the general magnitude of abstraction in the region. Also, they are previously unpublished and provide the basis used in far more recent studies including Lahmeyer's (2006) study and the IAEA's (2010) work.

What these data in conjunction with the literature review, fieldwork observations and interview findings clearly show is that smallholders using matara continue to be the major users of groundwater in the Dongola area (Fragaszy, 2014; Interviews, C, D). Increasingly, though, smallholders in basin areas not served by canal infrastructure as well as large operations owned by companies and absentee landowners are utilising deep boreholes to cultivate regions distant from the Nile. Given this pattern of expansion as well as local groundwater recharge characteristics and complex interactions between the NVA and NSA at their interface (Niestle, 1993; Abdo and Khalafall, 2000) it is safe to say that significant increases in abstraction from the NSA have occurred in recent years.

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[6] Even though agricultural land-use conflicts in the area were described as rare and not a generalisable problem, there is still great residual anger in the region over the flooding of Wadi Halfa following the completion of the Aswan High Dam. This conflict was re-ignited when the Merowe Dam flooded out local smallholders (some of whom had arrived after being relocated from Wadi Halfa). The new Kajbar Dam (north of Dongola) is expected to displace more people when the reservoir is filled (Interviews, 1, A, B).

Table 2. Total usage of groundwater in Northern State (Mm$^3$/year).

| District | Locality | Matara | | | Agricultural borehole | | | Municipal supply | Total abstraction |
|---|---|---|---|---|---|---|---|---|---|
| | | Functioning | Non-functioning | Production | Functioning | Non-functioning | Production | Production | |
| Dongola | Kerma | 1,472 | 672 | 56.25 | 1 | N/A | 0.21 | 1.17 | |
| | Argo | 5,658 | N/A | 252.7 | 8 | 2 | 0.48 | 1.26 | |
| | Hafir | 754 | 70 | 28.38 | N/A | N/A | N/A | 1.26 | |
| | Dongola city | 310 | N/A | 17.67 | 3 | 2 | 0.40 | 3.15 | |
| | Dongola East | 4,153 | 44 | 224.89 | 6 | 19 | 0.13 | 1.26 | |
| | Dongola West | 604 | N/A | 31.38 | 2 | 4 | 0.08 | 0.14 | |
| | Goled | 1,465 | N/A | 12 | 1 | 7 | 0.52 | 2.52 | |
| | Old Dongola | 935 | 432 | 18.61 | N/A | 3 | N/A | 0.58 | |
| | Total | 15,311 | 12,118 | 642.15 | 21 | 37 | 1.82 | 11.34 | 655.31 |
| Debba | Debba | 1,313 | 59 | 59.01 | N/A | N/A | N/A | 3.1 | |
| | Tadhamon | 861 | 135 | 19.42 | N/A | N/A | N/A | 10.07 | |
| | Ghaba | 338 | 712 | 12.5 | 1 | N/A | 0.14 | 1.68 | |
| | Total | 2,512 | 906 | 90.93 | 1 | N/A | 0.14 | 14.85 | 105.92 |
| Merowe | Karima | 142 | 0 | 5.8 | N/A | N/A | N/A | 0.01 | |
| | Zouma | 318 | 0 | 14.3 | N/A | N/A | N/A | 0.64 | |
| | Alarak | 226 | 0 | 11.97 | N/A | N/A | N/A | 0.44 | |
| | Merowe | 701 | 0 | 28.64 | 10 | 1 | 1.37 | 4.15 | |
| | Total | 1,427 | 0 | 60.71 | 10 | 1 | 1.37 | 5.24 | 67.32 |
| Wadi Halfa | | 125 | 0 | 4.95 | N/A | N/A | N/A | N/A | |
| Total | | 19,375 | 2124 | 798.74 | 32 | 38 | 3.33 | 31.43 | 833.5 |

Source: Northern State Ministry of Agriculture (1997).

Also, abstraction has almost certainly increased from the NVA areas which are not supplied by river pump infrastructure, the majority of cultivated area in the region. Anecdotal (Interviews, C-D) and modelled (Lahmeyer, 2006) evidence of declining water tables in Seleim areas not served by the canal supplements Niestle's (1993) conclusions that groundwater abstraction has outstripped annual recharge since at least the early 1990s in the Dongola region. Additionally, the volume of groundwater abstracted directly from the NSA will increase in direct proportion to the expansion of cultivation in the distant terraces where average well depth is far greater than basin areas close to the Nile (Abdo and Khalafall, 2000; Fragaszy, 2014).

The location of new farms in the study area has significant repercussions on the sustainability of groundwater-dependent irrigation. Due to geological differences, groundwater recharge occurs in highly dispersed manners, with Nile surface water influences on groundwater detected more than 40 km away from the river (Abdo and Khalafall, 2000). It has also been detected that deep wells (deeper than 100 m) more than 20 km from the Nile can exhibit similar influences in groundwater chemical and isotopic composition just as shallow wells near the Nile (Kheir, 1986). Also, wells in the same basin regions located less than 5 km apart that have screens of similar depth can tap water with widely different chemical and stable isotopic composition (Fragaszy, 2014). These complex interactions indicate that even shallow groundwater abstraction and irrigation in the low-lying basins can impact deeper Nubian aquifer horizons.

## DISCUSSION

This study highlights the myriad factors that encourage the expansion of and influence the location of new groundwater-dependent agricultural developments in the study area. This section summarises the study's findings and discusses their interaction with themes of wider interest including climate and land-use changes in the Nile Basin as well as a potential future Nile-sharing agreement.

### Factors contributing to groundwater-dependent irrigation expansion in Dongola

Study findings suggest that expansion of groundwater irrigation in Dongola is mainly encouraged by the fact that there has been no major expansion of surface irrigation works in the study region and none is likely forthcoming due to financial limitations. Rather, government attention has focused on repairing, maintaining and improving the operation of existing infrastructure that services the Seleim and other basin areas close to the Nile. The lack of additional surface irrigation forces older agricultural developments to utilise conjunctive surface water and groundwater irrigation and new developments in the Khway and desert terraces to rely on deep (100 m+) groundwater boreholes that tap the NSA.

In the study area, the historically cultivated flood-basin areas are nearly fully occupied and therefore allow intensification but not extension of arable area (Hamad, 2005). Patterns of land tenure preclude large holdings close to the river, encouraging cultivation in farther terraces. In the more distant Nile alluvial regions and desert terraces there are few competing interests and large areas can be agglomerated easily in contrast to basin areas where economies of scale are difficult to achieve due to landholding patterns.

Agricultural development in these marginal regions is capital-intensive due to the need for deep boreholes, efficient irrigation systems, electricity infrastructure and in some areas the ability to sustain low yields and potentially negative returns for several years. Recent infrastructural improvements including new road and bridge linkages with Khartoum and Port Sudan as well as the decreased cost and increased reliability of electricity supplies reduce farming costs in Northern State, particularly for large operations. Also, research has shown that areas with salinity-impacted topsoil layers can still be cultivated profitably given longer time horizons.

Sudanese central government policies neither emphasise nor provide significant direct incentives to groundwater-based irrigation. The relative high cost of groundwater development, the availability of surface water and history of failures of government-sponsored groundwater projects have combined to prevent the government from embarking on large-scale development of groundwater resources for agriculture. Rather, private actors including Sudanese landholders and companies as well as foreign agribusinesses are responsible for expanding cultivation in areas distant from the Nile. While political drivers and government subsidies incentivising self-sufficiency in staple crops like wheat have had some influence on groundwater-irrigation expansion, it is largely limited to government-run irrigation schemes, a small minority of landholdings in Northern State (El-Houri, 2007).

Because both Nile Valley cropping and basin flood-irrigation from the natural flood pulse is still such a large component of Northern State agriculture, available statistics on cultivated area show a wide interannual range that masks potential groundwater expansion trends (Northern State Ministry of Agriculture Statistics, 2003-2014). Wheat and alfalfa, the primary crops of large-scale groundwater-dependent farms, are grown in the basins as well, and their area of cultivation on an annual basis varies widely, often because of central government funding and subsidy mechanisms, and therefore they cannot be used as a proxy to determine groundwater-dependent irrigation expansion (Abdelrahman, 2012).

Groundwater aquifers are relatively well-mapped and characterised within the region and groundwater can be abstracted easily and in sufficient quantities to maintain large-scale cultivation. But the hydrogeological complexity of the region is a double-edged sword for the sustainability of the groundwater resource system. With careful well placement and irrigation management, groundwater-dependent irrigation can be sustainable because significant recharge to the NVA occurs and to a lesser extent the NSA also. Simultaneously, it indicates that anthropogenic pollution can impact groundwater quality.

Further research in the region should aim to improve understanding of groundwater abstraction quantities and cultivation expansion in areas reliant on groundwater through some combination of the following elements: structured and representative farm surveys, a census of wells, and a remote-sensing-based GIS analysis of cultivation in the region. In addition, hydrogeological investigations of the mechanisms and locations of mixing between the Nile Valley and Nubian Sandstone Aquifers will improve understanding of the groundwater resource and allow evidence-based planning for future development.

## Climate change, surface water and groundwater interactions, and the future allocation of Nile waters

All other factors held constant, climate change in Northern State itself will lead to a reduction in groundwater recharge, reduction in the main winter crop-growing season and increase in crop water requirements (Niestle, 1993; Ageeb, 1994; IFAD, 2013). Average temperatures during the flood season and main wheat-growing season (July to October and November to February, respectively), are expected to increase over one degree centigrade – and up to four degrees depending on the climate projection scenario (IFAD, 2013). Most of the regional groundwater recharge occurs during the flood peak and so any increase in evaporation will reduce groundwater infiltration (Niestle, 1993). Also, increased winter temperatures will reduce the already short wheat-growing season in Northern State and increase heat stress, both of which have negative impacts on crop yields (Ageeb, 1994).

Climate change in the Blue Nile headwaters will impact surface water and groundwater resources in Northern State as well. Blue Nile flow scenario analyses considering only precipitation changes generally suggest increased outflow over the next century ranging from +32 to -14% per annum (IFAD, 2013). However, Blue Nile outflow scenarios that incorporate increased irrigation within the Blue Nile catchment in Ethiopia and southern Sudan predict overall reduced flows into Lake Nasser. One major goal and expected benefit of upstream Blue Nile flow regularisation resulting from the GERD and other dams is to increase surface irrigation potential. As such, Blue Nile hydrological changes are difficult to predict because of the uncertainties in both climate and land-use change impacts on the water resource system (Elshamy, 2009; NBI, 2012). Like increased evaporation resulting from higher temperatures, any decrease in average Nile flood peak levels will necessarily reduce groundwater recharge in the flood-basin areas near Dongola (Niestle, 1993).

Given the present infrastructure and cultivation patterns shown in this study, major reductions in the flood pulse would result in corresponding agricultural output declines in Northern State. Nile Valley and flood-basin landholders outside of regions served by river pumps and canal infrastructure would be significantly affected by reductions in the Nile flood peak, and these groups cultivate the large majority of agricultural land in Northern State (El-Houri, 2007). While widespread food security risks in Northern State itself as a result of agricultural output declines are unlikely, the knock-on effects in the rest of Sudan would likely be very significant and reverberate throughout the nation in the form of food price rises and increased need to import staples (FAO, 2010). However, given that Northern State's populace includes critical constituencies of the Khartoum government, it is a key producer of staple crops and it also hosts major agribusiness interests, intervention to ameliorate the negative impacts of changing Nile hydrology in Northern State will likely be a high government priority (Verhoeven, 2012).

The development of extensive desert farming supplied by the NSA is a long-term possibility and has been included in previous Sudanese national development plans (Woertz, 2013). The GWG specifically mentions the suitability of major groundwater-fed cultivation expansion in wadi beds in the area (GWG, 2001). Also, several Gulf-based food importers have introduced plans to expand wheat and fodder cultivation in Northern State (Woertz, 2013a). However, interviewees described current foreign agribusiness investments in the Dongola area as small in scale relative to extant production, not threatening smallholders due to their location in the distant terraces or desert, and unlikely to increase in scale soon; confirmed and implemented major foreign agribusiness investment has focused in areas of northern Sudan more closely linked to national and export markets (Keulertz, 2013; Verhoeven, 2013; Woertz, 2013; Interviews, A, C-D). Unfortunately, the lack of hard data, political sensitivity and opacity of many purported agribusiness investment agreements make the actual implementation of such investments difficult to track, let alone to predict future patterns in Northern State (Verhoeven, 2013).

Although government investment in regional agriculture focuses heavily on Nile-based irrigation schemes, both government and privates-sector investments in major new Nile pump irrigation initiatives are not expected in the study area in the near future due to cost constraints and low productivity of available land in comparison with areas in central and southern Sudan (Keulertz, 2013). Ultimately, the primary issue of concern, should such extensive desert-irrigation expansion occur, would be its sustainability given the volume of active recharge to the NSA or its significant utilisation of Nile water resources given that Sudan is close to complete utilisation of its 18.5 $Bm^3$ after the filling of the Merowe Reservoir (Whittington et al., 2014). Therefore, like the issue of upstream dams' impacts on both surface water and groundwater resources in the study area, discussion of expanded NSA-reliant cultivation is still speculative though deserving of close monitoring.

At the basin level, interactions of surface water and groundwater represent an additional challenge when it comes to envisaging a new covenant for the allocation and sharing of Nile waters amongst its riparian users. The current 1959 Nile Waters Treaty does not include groundwater, but it is likely that in the future groundwater will be regulated in any new water-sharing treaty passed through the Nile Basin Initiative (NBI) negotiations or whatever its successor may be as they occur within the legal framework of the 1997 UN Convention on the Law of the Non-Navigational Uses of International Watercourses (Interviews, 1-2).

This Convention entered into effect in August 2014 and states in Part 1, Article II, that watercourses [such as the Nile] consist of the surface water and groundwater bodies to which they are hydraulically connected (UN, 1997). Still, groundwater usage from the NSA is not included in NBI negotiations (Interviews, 2-3, B) because the aquifer's development is currently monitored by basin countries Chad, Libya, Egypt and Sudan through the UNDP and IAEA's Strategic Action Plan that is building a scientific basis and political framework for transboundary Nubian Sandstone management (IAEA, 2013). Considering the potential uncertainty of future Nile allocations after the conclusion of the NBI negotiations and even the river's hydrological regime given projected climate changes, upstream dam building programmes and potential land-use changes, groundwater utilisation should be seen both as a vital long-term development resource and as a short-term buffer against the political and hydrological vagaries of the Nile.

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Interview 3. Official from the Ministry of Water Resources and Electricity; member of Sudan's Nubian Sandstone Regional Strategic Action Programme Committee (Khartoum). Interview conducted on 30 March 2014.

Interview 4. Senior official from the Groundwater and Wadis Directorate responsible for groundwater resource data collection and monitoring (Khartoum). Interview conducted on 31 March 2014.

Interview 5. Official from the Ministry of Agriculture responsible for agricultural data collection and monitoring (Khartoum). Interview conducted on 18 April 2014.

Interview 6. Senior official from the Ministry of Agriculture responsible for state-level policy implementation (Dongola). Interview conducted on 13 April 2014.

Interview 7. Official from the Ministry of Agriculture responsible for agricultural data collection and monitoring and farmer extension services (Dongola). Interview conducted on 14 April 2014.

Interview 8. Professor from the University of Khartoum, Faculty of Agriculture whose research focuses on soil salinization and remediation. Interview conducted on 28 March 2014.

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