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Enhancing Water Sustainability in North Africa: Literature Review and Synthesis of Current Knowledge Gaps in Sudan

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Enhancing Water Sustainability in North Africa: Literature Review and Synthesis of Current Knowledge Gaps in Sudan

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Abstract. This study delves into the critical role of groundwater in addressing global water challenges, with a focus on the Nubian Sandstone Aquifer System (NSAS) in North Africa. Groundwater constitutes a source of potable water, irrigation, and industrial use, especially in arid regions where surface water is limited. We analyzed the status of water quantity, withdrawals, recharge, and geological characteristics in the NSAS, specifically in Sudan, Egypt, Libya, and Chad. Though the NSAS is largely an untapped resource, we evaluated various scenarios to determine the quantity of cropland that can be sustainably irrigated. The NSAS is located in an arid region, so local recharge does not exceed 10 mm/year. The primary source of recharge comes from the River Nile. The annual recharge is the following: Sudan Platform: 1.44 ± 0.42 km^3/yr, Dakhla: 0.135 km^3/yr, Kufra: 0.78 ± 0.49 km^3/yr. Withdrawal rates are as follows: Egypt: 1.029 km^3/yr; Libya: 0.851 km^3/yr; Sudan: 0.406 km^3/yr; and Chad: 0.001 km^3/yr. The amount of water in the (NSAS) in North Africa is estimated at approximately 150,000 km^3. This volume is equivalent to about 500 years' worth of the Nile River's discharge. The NSAS is the most extensive fossil aquifer complex globally underlying an area of 2,200,000 km^2. The findings contribute valuable insights for policymakers, researchers, and communities grappling with the challenges of groundwater resources to face climate change and water demands.

Keywords. *Arid region, Fossil aquifer, Groundwater, NSAS, North Africa, Recharge, Sustainability, Withdrawals.*

The Critical Role of Groundwater in Addressing Global Water Challenges

Water covers three-quarters of the Earth's surface, and it is also found under the Earth's surface everywhere and at different depths underground (Margat & Van, 2013). The general public has limited understanding and knowledge about groundwater (Margat & Van, 2013). In many arid and semi-arid regions, groundwater is the main source of drinking water (supplying half the world's population), irrigation, and thus food security (Margat & Van, 2013). Over 97% of the water in the world is unusable salt water; most freshwater is inaccessible and frozen in glaciers and ice caps (Gaglio, 2017). Aquifers are layers of unconsolidated and consolidated materials, such as sand and sandstone, typically bounded by an impermeable layer (Gaglio, 2017). Unlike traditional surface water sources, aquifers are not readily replenished, and there is no alternative to water (unlike fossil fuels) (Gaglio, 2017). Aquifers are the second largest source of freshwater, and about 99% of it is stored in various underground aquifers (Gaglio, 2017).

Groundwater is very important worldwide. Many people depend on groundwater for domestic, industrial, and agricultural purposes, especially in desert areas, where there are no adequate surface water supplies. It provides about 50% of potable water supplies, 30% of industrial water, and 20% of irrigation water worldwide, but in some desert countries (Saudi Arabia) groundwater contributes 79% of the total water supply (El-Rawy et al., 2021). The quality of groundwater provides a good description of water usability, according to the World Health Organization. The groundwater suitability for irrigation depends on the effect of mineral components that are present in plant water and soil (El-Rawy et al., 2021). The variability of spatio-temporal climate change affects groundwater systems directly through recharge and indirectly through changes in groundwater use. The processes of replenishment of groundwater occurs through recharge, which is dependant on climate, land cover, and geology. Climate and land cover control precipitation and evaporation, while geology controls water transport through the soil and its storage and transport from the surface and subsurface into aquifers. Climate change will have both quantitative and qualitative effects on groundwater resources. These impacts differ for aquifers in solid and unconsolidated rock, in urban or rural locations, and in the principal processes of groundwater recharge (Epting et al., 2021). Groundwater contamination results in diminished groundwater accessibility, with chemical and biological pollutants being the primary contributors to 80% of diseases and fatalities in developing nations. (El-Rawy et al., 2021). Information from the World Health Organization indicates that more than 1 billion people do not have access to clean drinking water and that 4,000 children die every day from diseases transmitted by contaminated water (El-Rawy et al., 2021).

Many aquifers are facing the significant challenge of over-pumping, which has various environmental and societal impacts (Taniguchi, 2011). Some of the most prominent aquifers around the world include the Ogallala Aquifer in the United States, the Guarani Aquifer in South America, the Nubian Sandstone Aquifer System (NSAS) in North Africa, and the Indus Basin Aquifer in South Asia (Van, 2022). They help sustain ecosystems by feeding streams and rivers and are particularly crucial in arid and semi-arid regions where surface water sources may be limited. The Ogallala Aquifer sustains farming activities and countryside settlements in eight U.S. states, yet various regions of the aquifer are experiencing a reduction in water levels (Lauer et al., 2018). The decline persists despite multiple institutional and political measures, suggesting that efforts in research and policymaking have not led to the tangible preservation of this essential shared resource (Lauer et al., 2018). Overall, the Ogallala Aquifer in the United States, also known as the High Plains Aquifer, has been experiencing depletion primarily due to extensive agricultural irrigation. The demand for water in the region, especially for crop irrigation, has led to significant withdrawals which is a major concern for the sustainability of agriculture in the region. In regions experiencing heightened and prolonged droughts, the ongoing exhaustion of aquifers will be hastened (Espindola et al., 2022). This challenge will be amplified by swift urban growth, escalating the need for water in cities, and the reinforcement of the prevailing dominant economic development model, which can only expand by elevating water consumption (Espindola et al., 2022).

Overall, the Guarani Aquifer in South America spans across Brazil, Argentina, Paraguay, and Uruguay. Population growth and increased agricultural activities are contributing to the depletion of this transboundary aquifer. Over-extraction for irrigation, industrial, and domestic purposes is putting stress on the Guarani Aquifer system. The Guarani Aquifer System(GAS) stands as one of the most expansive subsurface water reserves globally, enveloping 1.1 million km^2 and lying beneath portions of four nations in the central-eastern region of South America (Sugg et al., 2023). The freshwater storage capacity of the GAS amounts to roughly 30,000 km^3, classifying it among the largest aquifers worldwide in terms of volume (Sugg et al., 2023). Comprising Mesozoic sandstones varying in thickness from under 50 meters to over 800 meters, the aquifer is predominantly enclosed by basalt layers (Sugg et al., 2023). However, there are approximately 125,000 km^2 of exposed zones along the periphery, encompassing areas of both replenishment and discharge (Sugg et al., 2023). This aquifer system consists of two sub-basins: the Central Paraná and the southwestern Chaco–Lower Paraná. The inherent quality of natural groundwater is generally deemed excellent, with an estimated 90% considered potable (Sugg et al., 2023). The GAS operates on a 'storage dominated' principle, where the annual natural recharge of approximately 45–55 km^3 is less than 0.2% of the total freshwater storage in the GAS. Present withdrawal rates stand at around 1.04 km^3 per year, with Brazil accounting for about 94%, Uruguay for 3%, Paraguay for 2%, and Argentina for 1%. The utilization of GAS groundwater is predominantly urban, with major applications allocating 66% for public water supplies, 16% for industrial purposes, and 13% for recreation and tourism (Sugg et al., 2023).

The lack of coordinated management among the countries sharing the aquifer poses additional challenges. In the case of the Indus Basin Aquifer in South Asia, given the arid and semi-arid climate prevalent in Pakistan, agriculture heavily relies on irrigation from both canals and aquifers (Watto & Mugera, 2016). Nevertheless, there's been a gradual decrease in surface water availability, with a 15% reduction over the last decade (Watto & Mugera, 2016). The scarcity of surface water isn't just a matter of insufficient supply; it's also becoming temporally and spatially unavailable in numerous areas within the Indus Basin (Watto & Mugera, 2016). The Indus Basin holds the dubious distinction of being recognized as the most depleted river basin globally in terms of surface water supplies (Watto & Mugera, 2016). Despite the escalating demand for irrigation driven by agricultural intensification, the likelihood of an increase in supply from surface water sources is minimal (Watto & Mugera, 2016). The demand for domestic and industrial water is estimated to grow at an annual rate of 10% in Pakistan (Watto & Mugera, 2016). Consequently, there has been a notable surge in the utilization of groundwater resources to sustain agricultural productivity amidst the escalating competition across different sectors (Watto & Mugera, 2016). Over-pumping, or excessive withdrawal of water from aquifers, occurs when the rate of water extraction exceeds the rate of natural recharge (refilling). This can result from various factors, including increased water demand, population growth, and inefficient irrigation practices. In coastal areas, excessive withdrawal can allow saltwater to intrude into freshwater aquifers, rendering the water undrinkable and damaging ecosystems (Shimada, 2011). Overall, unsustainable water usage practices, population growth, and inadequate management contribute to the depletion of these prominent aquifers, highlighting the need for effective groundwater conservation and management strategies in the most prominent aquifers around the world.

Current Status of Water Quantity, Withdrawals, and Recharge in the Nubian Sandstone Aquifer

Water Quantity

The growing role of aquifers in Africa is that it represents an important source for meeting the basic needs of life and human development. It is the only reliable source of water in many parts of Africa, a perennial source of water, and provides a buffer in times of drought (Nijsten et al., 2018). Africa's dependence on groundwater resources, specifically transboundary aquifers, has become increasingly critical for sustaining livelihoods, and economic development. Groundwater serves as a primary source of drinking water for approximately 75% of Africa's population (Nijsten et al., 2018). Beyond meeting drinking water needs, groundwater plays a pivotal role in driving economic growth and supporting agriculture. It enables irrigation, sustains rural communities, and forms the backbone of urban water supply systems. During drought, it serves as a cost-effective and dependable water source, aiding in economic stability. Understanding how much water is in the NSAS is crucial to ensure sustainable management of this vital water resource. This will help determine how much water can be withdrawn without depleting the aquifer beyond its natural recharge rate (Sefelnasr et al., 2015).

Transboundary Aquifers cover a substantial portion of Africa, spanning 40% of the continent's land area and accommodating 33% of its population (Nijsten et al., 2018). These aquifers are located in areas with high storage and aquifer yields, making them essential for Africa's development. As Africa confronts mounting pressures on its groundwater resources due to population growth, climate change, and economic expansion, sustainable management of these resources takes on greater significance. This management is necessary to ensure equitable access to groundwater and secure its long-term availability. Historical international cooperation efforts in managing Transboundary Aquifers in Africa date back to the 1970s.

Today, Africa boasts 72 Transboundary Aquifers on its mainland (Nijsten et al., 2018). Collaboration among neighboring countries is crucial for addressing resource allocation disparities and varying management capabilities. Comprehensive monitoring and assessment are essential for understanding aquifer characteristics, evaluating environmental impacts, and considering socio-economic dimensions. Standardized data collection and harmonization of monitoring systems across borders are emphasized. Several Transboundary Aquifers in Africa have agreements for joint management, reflecting progress in the governance of shared aquifer resources and the extent and effectiveness of these agreements can vary, with domestic legal and institutional frameworks playing a significant role in resource management (Nijsten et al., 2018). The NSAS, shared by Egypt, Libya, Chad, and Sudan, stands the world's largest aquifer (Nijsten et al., 2018). It highlights the importance of cooperation among aquifer states, given its immense freshwater reserve. Agreements among these countries underscore the significance of monitoring, data sharing, and collaborative efforts to ensure the sustainable use of this vital resource (Nijsten et al., 2018).

The future of people's lives in the countries of this region is similar because they live in an arid desert region and depend on the groundwater aquifer most of the time. The groundwater of the Nubian aquifer has been identified as the only source capable of meeting the needs of the people of this region for fresh water and development goals in the future (Sefelnasr et al., 2015). It can facilitate cooperation and agreements for equitable usage of water resources and educate people about the importance of water conservation in regions where multiple countries share access to the NSAS because the International Law Association sources create a clear framework for the utilization and management of transboundary aquifers (Gaglio, 2017). Since the early Paleozoic time in this region, the vertical movement has been very slow and is of an epeirogenesis nature (Sefelnasr et al., 2015). This led to the formation of the large basins of the region, which were filled with sediment, with a thickness up to 4,500 meters, separated by zones of minor subsidence or uplift (Sefelnasr et al., 2015).

The NSAS consists of three main sub-basins: Al-Kafra, Dakhla, and the North Sudan Platform (Mohamed et al., 2022). The flow of groundwater through the sub-basins of the Nubian aquifer, and the connection between its sub-basins and its hydrological status are currently unclear (Mohamed et al., 2022). The status of water quantity in the NSAS is a matter of concern due to increasing demand and the potential impacts of climate change. The flow of groundwater is from the south, where there are natural highlands and rainfall, to the north, where the outcrops of the Nubian sandstone aquifer are located (Mohamed et al., 2022).

The NSAS in North Africa stands as the continent's most expansive fossil aquifer complex, boasting a groundwater capacity estimated at 150,000 km^3, equivalent to approximately 500 years' worth of the Nile River's discharge (Geriesh et al., 2023). El-Rawy et al (2021) pointed out that the overall groundwater storage volume within the NSAS in 1960 was estimated to be 150,000 km^3, underscoring a substantial groundwater resource. Field observations, Geographic Information System (GIS), and complex statistical examinations (Factor analysis) were employed to evaluate the groundwater characteristics of the NSAS (El-Rawy et al., 2021). A total of 144 groundwater specimens were gathered and scrutinized for predominant ions and trace constituents, while the spatial dispersion of physicochemical attributes was depicted using GIS (El-Rawy et al., 2021). The findings were utilized to assess groundwater quality for potable and agricultural utilization, compared with the standards set by the World Health Organization (WHO) and Egyptian Water Standards (El-Rawy et al., 2021). The outcomes unveiled that 93.8% of the groundwater samples were categorized as fresh, with Total Dissolved Solids (TDS) levels below 1000 mg/L, while the remaining 6.2% exhibited slight salinity (TDS ranging from 1000 to 3000 mg/L) (El-Rawy et al., 2021). The computed water quality index suggests that 88.2% of the specimens meet the criteria for excellent suitability for drinking purposes. As per the Soluble Sodium Percent (SSP) standards, 46% of the samples exhibit water quality suitable for irrigation, while 71% meet the requirements based on sodium content and 79.2% demonstrate suitability based on permeability index (PI) alues. Furthermore, 91.1% of the samples are deemed suitable for irrigation considering the magnesium hazard (MH) values (El-Rawy et al., 2021).

Functioning as the planet's largest transboundary aquifer, the NSAS is jointly managed by Egypt, Libya, Sudan, and Chad, encompassing a vast geographical expanse of around 2,200,000 km^2 (Mohamed et al., 2022). This area is distributed as follows: Egypt: 828,000 km^2 (38%); Libya: 760,000 km^2 (34%); Sudan: 376,000 km^2 (17%); and Chad: 235,000 km^2 (11%) (Moghazy, 2021). The NSAS has a maximum depth of 4500 meters, and hydraulic head fluctuations range from 570 meters above mean sea level in the western region of Darfur, Sudan, to -78 meters below mean sea level in Egypt's Qattara Depression (Geriesh et al., 2023). The freshwater layer within the aquifer system possesses a thickness spanning from 200 to 3500 meters, characterized by medium to good hydraulic properties (Geriesh et al., 2023). In Egypt, the NSAS contributes a substantial water storage of 40,000 km^3; however, this reserve is deemed non-renewable due to the limited groundwater recharge in the Western Desert (Geriesh et al., 2023). The typical direction of underground water movement of the NSAS is from the southwest to the northeast (Abdelmohsen et al., 2019).

The predominant composition of groundwater samples of the Nubian sandstone aquifer within the region spanning from southern Aswan to northern Sudan predominantly falls under the freshwater category, with concentrations measuring below 1000 parts per million (ppm), as delineated by Ghoubachi (2012). These concentrations exhibit a gradient from 229 ppm in the southern reaches to 990 ppm in the northern extents Ghoubachi (2012). The salinity of the groundwater escalates in the northwest direction, aligning with the flow of groundwater, and this escalation is attributed to the extensive intercalation of clay deposits (Ghoubachi, 2012). Over time, the salinity of this water probably diminishes, largely due to the infiltration of freshwater from Lake Nasser (Ghoubachi,2012). Positioned to the south of Aswan in southern Egypt and to the north of Wadi Halfa in northern Sudan, Lake Nasser stands as one of the largest man-made lakes globally. According to the findings of Ghoubachi (2012), the volume of water seeping from Lake Nasser amounts to approximately 24×10^6 m^3/y.

Surface water resources in these zones are adversely affected by elevated evaporation rates. Given these circumstances, groundwater emerges as the sole viable water source in these arid regions. The Sudanese territories are predominantly characterized by groundwater aquifers, including the Nubian aquifer, the Um Ruwaba formation, the alluvial aquifer, and the hard rocks aquifers (Mohamed, 2020). These four primary aquifers encompass approximately half of the Sudanese region's total surface area. The most extensive of all of them is the Nubian Aquifer, which constitutes over 28% of Sudan's surface area (Mohamed, 2020). Comprising sandstones, this aquifer is shaped by nine major basins, including the Nile basin, Sahara basin, Atbara basin, Blue Nile basin, central Darfur basin, Gedaref basin, Nuhud basin, Shaggara basin, and Sag El Naam basin (Mohamed, 2020). The saturated layers within the aquifer exhibit varying thickness, ranging from 100 to 2000 meters, with a permeability that ranges from low to moderate, ensuring good water quality (Mohamed, 2020).

From a hydrogeological perspective, the Nubian Formation in the Aswan area consists of three horizontal units with a collective thickness of 0.4 km (Khalil & Santos, 2013). The bottommost unit, situated above the granitic basement, constitutes an aquifer of fluvial sandstones with a large-scale (spanning several km) horizontal permeability. The middle unit functions as an aquiclude, extending uninterrupted beneath the lake but exhibiting intermittent "leakage" over periods extending to several years. This lower aquifer remains confined for extended durations, typically lasting several years. The uppermost unit represents the water table aquifer, composed of sandstone with a porosity of 25–30%, interspersed with clay stone lenses. Reports indicate varying Nubian sandstone porosity values, ranging from 20% to 45%. (Khalil & Santos, 2013).

The hydraulic conductivity of a substance can be described as its ability to allow the passage of fluid through the pores and fractures within rocks, sand, or other porous media. This conductive property is influenced by the specific characteristics of the aquifer present in the given area (Mohamed, 2020). Groundwater moves from areas with higher hydraulic head to those with lower hydraulic head (Mohamed, 2020). The alteration in hydraulic head along the path of groundwater flow is referred to as the hydraulic gradient, encompassing both magnitude and direction (Mohamed, 2020). The speed of groundwater movement correlates with the size of the hydraulic gradient and the hydraulic conductivity of the aquifer (Mohamed, 2020). In locations with larger hydraulic gradients and/or higher hydraulic conductivity, groundwater tends to flow more rapidly (Mohamed, 2020). Compared to surface water, groundwater flow rates are notably slower, except in limestone karst formations, where it traverses caves and substantial solution channels (Mohamed, 2020). Although the speed of groundwater flow varies widely, it typically remains within a few meters/day (Mohamed, 2020). The hydraulic conductivity for the Nubian sandstone aquifer (western bank of River Nile, Aswan area) is estimated to be 12.6 ± 1.9 m/day (Khalil & Santos, 2013).

A thickening of the sedimentary cover in the NE-SW direction from the southern Kufra through the northern Kufra to the Dakhla subbasin and the sedimentary cover was found to increase from less than 0.5 km in the south (Northern Sudan and Uweinat region) to more than 6 km in the north (Mediterranean coast) (Mohamed & Abdelrady., 2023). A large Pelusium megashear system that runs northeast to southwest makes it easier for groundwater to flow from the Kufra subbasin to the Dakhla subbasin (Mohamed & Abdelrady., 2023).

The NSAS, a vital groundwater resource, exhibits a distinctive flow pattern predominantly from the south and southwest to the north and northeast (Geriesh et al., 2023). Several factors contribute to this hydrological behavior. Firstly, the substantial variation in sedimentary layer thickness plays a pivotal role. Beginning in the southern reaches, particularly Northern Sudan, the sedimentary layer measures around 500 meters but dramatically escalates to over 6,000 meters as one traverses northward, culminating at the Mediterranean coast (Mohamed & Abdelrady, 2023). In the southern parts of the Nubian Sandstone Aquifer System, the geological composition is primarily characterized by rocks and clay soil. However, interspersed within this terrain are pockets of sand at varying depths, notably observed in regions extending from northwest Sudan to Southwest Sudan, such as the Bara basin and the western part of the White Nile. Additionally, the Kufra basin in Northern Chad and Southeast Libya showcases a similar geological makeup.

Recharge

Historical recharge

Historical recharge in the NSAS is generally attributed to past climatic conditions and geological processes. During previous humid climatic periods, the NSAS was recharged on a regional scale. During drought periods, the outcrops of the NSAS received modest local recharge (Mohamed et al., 2022). Recharge of the NSAS occurred several thousand to millions of years ago due to the strengthening of ancient monsoons or historical westerly winds, and theories suggest that the primary source of replenishment and recharge was rainfall from distant mountains in the southwestern regions like Ennedi, Erdi, and Tibesti (Mohamed et al., 2022).

Geriesh et al.(2023), indicated that the age of groundwater in the NSAS varies from under 30,000 years in the southern region to one million years in the northern part. The Earth's climate has experienced numerous fluctuations over the past 2.6 million years, encompassing the Quaternary Period (Mohamed et al., 2022). It has alternated between glacial and interglacial phases. Notably, significant ice ages and interglacial periods have occurred approximately every 100,000 years within the last million years (Mohamed et al., 2022).

While presently, the northwestern part of Sudan and the southwestern part of Egypt stand among the driest regions in the Sahara, archaeological evidence linked to remnants of playa or lake deposits unveils historical periods characterized by elevated effective moisture (Mohamed et al., 2022). Geoarchaeological studies conducted at Neolithic playa sites in Egypt and ancient lakebed sites in northern Sudan generally depict a pluvial cycle during the early Holocene (Mohamed et al., 2022). According to King-Okumu (2021), a comprehensive groundwater flow model, employing GIS on a significant scale, was applied to the NSAS situated in the Eastern Sahara region (comprising Egypt, northern Sudan, and eastern Libya), revealed that the aquifer's groundwater originated from infiltration during periods of increased moisture around 20,000 and 5,000 years b.p (before present or before AD). It's crucial to recognize that the NSAS is considered a non-renewable or slow-renewable resource. The water stored in the aquifer accumulated over geological epochs, and the current extraction rates are much higher than the natural recharge rates, leading to concerns about the sustainability of water use from this aquifer. Therefore, managing and conserving this finite resource is essential for the long-term sustainability of water availability in the region.

Current recharge

Local recharging of the Nubian sandstone aquifer does not exceed 10 mm/year (Mohamed et al., 2022). The mean yearly rainfall across the recharge regions within the sub-basins of South Kufra and North Sudan Platform has been approximated at 54.8 and 32.8 km^3, correspondingly, using data from the Tropical Rainfall Measuring Mission (TRMM). Gravity Recovery and Climate Experiment (GRACE) data affirm significant recharge rates of 0.78 ± 0.49 and 1.44 ± 0.42 km^3/y in the South Kufra and North Sudan Platform sub-basins, respectively (Mohamed et al., 2022). Analysis of groundwater fluctuations, combined with environmental isotopes, suggests that the primary source of recharge comes from the River Nile, supplemented by the underflow from the Blue Nile basins. The annual recharge from the major basins 1.381 km3/year (Omer, 2002). The annual replenishment flow originating from Lake Nasser in Egypt was approximated at 0.135 km^3/y, which can contribute to the restoration of groundwater levels in the Tushka region (Mohamed et al., 2022).

In the timeframe spanning April 2002 to July 2016, fluctuations in groundwater storage were approximated at 8.38 ± 2.68, 7.64 ± 1.42, and 0.77 ± 1.07 km^3/yr for the overall Sudanese region, the Northern Sudan segment, and the Southern Sudan segment, respectively (Mohamed, 2020). The Sudanese region, Northern Sudan, and Southern Sudan experience substantial average annual precipitation levels, standing at an estimated 520.2, 300.3, and 1165.6 mm/yr, respectively (Mohamed, 2020). Notably, heightened recharge rates were calculated at 10.39 ± 2.68 and 8.85 ± 1.42 km^3/yr for the Sudanese region and Northern Sudan sections, respectively. Conversely, the Southern Sudan section, primarily characterized by extensive basement rocks in the southern and southwestern regions, exhibited minor recharge of +1.56 ± 1.07 km^3/yr (Mohamed, 2020).

All governments of countries in the Middle East and North Africa, including countries that have permanent rivers, have invested in building hundreds of dams to support rainwater harvesting and increase groundwater recharge, as increasing recharge through reservoirs and recharge dams is considered an effective tool to supplement water resources by collecting water floods, which are usually drained into the sea and desert (Sherif et al., 2023).

Withdrawals

Withdrawals from the NSAS have been a subject of concern due to the increasing demand for water resources in the region. Agricultural, industrial, and domestic water needs have led to significant withdrawals, raising issues related to sustainability and potential long-term consequences for the aquifer system. The rate of groundwater extraction needs to be carefully managed to prevent overexploitation and depletion. The Sahara Nile basins, also known as the Nubian basins, encompass the northern part of the northern Kordofan state, stretching from north of Khartoum to the Egyptian border, covering a total area of 273,980 km^2. The geological formations in this region consist of the Nubian sandstone formation and the basement complex (Omer, 2002). In most Middle Eastern and North African countries, groundwater withdrawals far surpass the natural renewal capacity, with renewability rates spanning from 6% to 100% in a few nations. This variability is shaped by factors such as total groundwater extraction, climate conditions, hydrogeological settings, and the state of water infrastructure throughout the region. (Sherif et al., 2023). The availability of freshwater resources essential for sustaining agricultural output is exceedingly restricted within this geographical area (Sherif et al., 2023).

In the arid expanse of North Africa, the NSAS plays a pivotal role in regional development, particularly within Egypt's Western Desert (King-Okumu & Abdelkhalek., 2021). These aquifers stand as the exclusive wellspring for the area's water demands. Intriguingly, as water resource management and utilization strategies progress in the Egyptian sectors of NSAS, the dynamic and renewable facets of the aquifer system undergo a rapid and transformative evolution. The utilization of NSAS in the Western Desert of Egypt commenced in the early 1960s, aiming to enhance agricultural output (King-Okumu & Abdelkhalek., 2021). Groundwater extraction was initiated at five distinct locations—Kharga, Dakhla, Farafra, Bahariya, and Siwa Oases—catering to both agricultural and domestic needs (King-Okumu & Abdelkhalek., 2021). In 1990, a new agricultural zone emerged, fueled by groundwater sourced from East Oweinat (King-Okumu & Abdelkhalek., 2021). The intense groundwater withdrawals from the NSAS in Libya and Egypt represent extraction from non−renewable groundwater reserves (Sherif et al., 2023). Groundwater stress is the ratio between groundwater abstraction and adjusted groundwater recharge, including the recharge fraction that is reserved to meet environmental flows (Sherif et al., 2023). As of 2012, the recorded withdrawal rates from the NSAS are as follows: Egypt:1.029 km^3/yr; Libya: 0.851 km^3/yr; Sudan : 0.406 km^3/yr; and Chad: 0.001 km^3/yr (Geriesh et al., 2023). Anticipated projections indicate that the total groundwater extraction from the NSAS is set to reach volumes in millions of km^3 (Geriesh et al., 2023).

Projections indicate a global surge of 40% in water demand by 2030 (Mohamed, 2020). Furthermore, this region faced freshwater depletion in the 1970s, resorting to external water sources through food imports. Anticipated population growth in North Africa is set to surpass 430 million by 2025, a significant increase from the current 311 million and approximately 100 million in 1960 (Mohamed, 2020). This demographic shift raises concerns about per-capita water averages, which are reaching alarming levels. This area faces challenges of water scarcity and inefficient water utilization in agriculture, (only around 40% efficiency reported) (FAO, 2003) (Mohamed, 2020). The primary replenishment for the northern Khartoum and north Kordofan basins stems from the Nile River and the subterranean flow originating from the Blue Nile basin (Omer, 2002). The discharge from this basin is projected to be approximately 0.0073 km^3 at Sudan's northern border (Omer, 2002). Three areas show considerable promise and are suggested for more extensive investigations: (Wadi El Mugadam), (Wadi El Qa'ab), and (Wadi El Khuewi and Wadi El Seleim (Omer, 2002). A significant challenge contributing to the groundwater flow dynamics to the North is the excessive withdrawals in the northern sector of the NSAS, specifically in the Dakhla basin. This overexploitation poses a threat to the sustainability of the aquifer, impacting the overall balance of groundwater distribution within the system. Furthermore, the northern part of the NSAS, particularly the Dakhla basin region, experiences a high evaporation rate due to elevated temperatures. This climatic factor exacerbates the challenges posed by excessive withdrawals, as it intensifies the demand on the aquifer while simultaneously diminishing the replenishment potential.

The NSAS faced a weak depletion in terrestrial water storage at a rate of −0.89 ± 0.11 mm/yr (equivalent to −1.87 ± 0.21 km^3/yr) during the period (2002 - 2020). Nevertheless, from April 2002 to December 2013, the NSAS experienced more significant terrestrial water storage (TWS) depletion at a moderate rate of −2.59 ± 0.71 mm/yr (−5.16 ± 1.41 km^3/yr) and −3.29 ± 0.29 mm/yr (−6.55 ± 0.57 km^3/yr). This was followed by a weak terrestrial water storage wetting trend (0.99 ± 0.53 mm/yr; 1.98 ± 1.05 km^3/yr) during the period (January 2014–September 2019) (Ahmed, 2020). Ensuring the sustainable utilization of groundwater resources in northern Africa poses significant challenges due to the fact that many of the aquifer systems in the region extend across country borders (Ahmed, 2020). Projections indicate a decrease in rainfall rates and associated recharge rates, while the population and the consequent strain on groundwater resources are anticipated to rise. In this region, on-site observations are severely constrained, both in terms of their availability and quality (Ahmed, 2020). Establishing and maintaining field networks covering the entirety of northern Africa would be economically impractical and demand extensive labor. Thankfully, data on terrestrial water storage obtained from the Gravity Recovery and Climate Experiment (GRACE) and GRACE-FO missions offer a cost-effective and efficient means to monitor groundwater resources in northern Africa and formulate sustainable management strategies for the region (Ahmed, 2020).

Climate change

The looming specter of climate change casts a shadow over the NSAS threatening its sustainability and reliability of the NSAS. Climate variability will bring quantitative and qualitative effects to subterranean water reservoirs (Epting et al., 2021). These alterations vary depending on whether the aquifers are situated in compact or loose rock formations, within urban or rural settings, and in the primary mechanisms governing the groundwater recharge. Understanding the aquifer geometries, their storage characteristics, rates of groundwater replenishment, durations of residence, and other pertinent factors, alongside recognizing the principal mechanisms facilitating groundwater replenishment and the influence of temperature changes, enables us to evaluate and predict the susceptibility of specific aquifers to climate fluctuations (Epting et al., 2021). In a projected climate change scenario at the conclusion of the century, alterations in precipitation patterns and occurrences of river floods might transition from summer to winter months. This shift could coincide with heightened groundwater replenishment during cooler seasons, potentially resulting in a trend of groundwater resources experiencing a cooling effect (Epting et al., 2021). There is a consensus that deep underground water reservoirs take a considerable amount of time to show noticeable changes in response to climate shifts (Abdelmohsen et al., 2019). The areas responsible for replenishing the Northern Sudan Platform subbasin went through a period of low precipitation from 2002 to 2012, with an average annual rainfall of only 85 mm. This was succeeded by a period of increased rainfall from 2013 to 2016, with an average annual precipitation of 107 mm (Abdelmohsen et al., 2019). Throughout both periods, the annual precipitation over the northern parts of the NSAS remained extremely low, consistently below 10 mm (Abdelmohsen et al., 2019). Instances of prospective fossil aquifers that might be explored for a comparable swift reaction to climate fluctuations encompass the Saharan aquifer systems in North

Africa and those in the Arabian Peninsula (Abdelmohsen et al., 2019).

The alteration in climate conditions contributes to the impact on groundwater reservoirs, with a worldwide trend toward rising temperatures and reduced precipitation levels, and groundwater reservoirs encounter challenges in numerous global areas, stemming from various influences such as pollution, saline intrusion, and extensive utilization, (Mohamed, 2020). The susceptibility of the North Africa region to climate change arises from its arid nature and limited water reservoirs. Escalating population figures, burgeoning economies, and alterations in land utilization patterns are exerting considerable pressure on freshwater reservoirs, significantly impacting the socio-economic potential of the area (Mohamed, 2020).

In rural Africa, the majority of domestic water supply and irrigation crucial for poverty reduction comes from groundwater (MacDonald et al., 2011). While climate change and population growth pose threats to water resources, groundwater responds more slowly than surface water, offering a potential buffer for adaptation strategies (MacDonald et al., 2011). Groundwater's reliability, sustained even during low rainfall, makes it advantageous. It acts as a vast natural water store, surpassing the capacity of surface water reservoirs (MacDonald et al., 2011). Climate models project consistent warming in Africa but uncertain rainfall patterns. Higher temperatures will increase evapotranspiration and alter rainfall intensity, impacting runoff and groundwater recharge (MacDonald et al., 2011). To adapt to these changes, relying more on groundwater becomes crucial for both small-scale and large-scale irrigation, as well as for reliable urban water supply. Despite the acknowledged benefits of groundwater, there's limited knowledge about African groundwater resources and their response to climate change, contributing to uncertainty in global assessments (MacDonald et al., 2011). The average earth's surface temperature will increase by 1.5˚C through 2030 to 2052 over the world, and agricultural production can be reduced by 15-25% due to climate change, which will pose a major challenge to the world regarding the problem of food security (Sahoo & Govind, 2022). The profound climatic occurrences, including floods, droughts, and windstorms, triggered by climate change, significantly affect the food security situation in Africa (Sahoo & Govind, 2022).

Sustainability of the Nubian Sandstone Aquifer Systems

The NSAS in Egypt, exemplified by the Dakhla sub-basin, is currently undergoing groundwater depletion. To achieve sustainable groundwater use in this specific case, it is essential to reduce the average withdrawal rate by 1.50 km^3/yr (Ahmed, 2020). In contrast, the overall health of the entire NSAS including the Kufra sub-basin in Libya, northeastern Chad, northwestern Sudan, and the northern Sudan sub-basin in northern Sudan—is robust, and current rates of groundwater extraction are deemed sustainable (Ahmed, 2020). Implementing effective management practices to mitigate groundwater depletion in this region involves various strategies, including but not limited to reducing irrigated areas and well drilling, substituting conventional crops with drought-tolerant alternatives, implementing groundwater allocation for each acre of farmland, transitioning from conventional flood to sprinkler irrigation systems, adopting modern irrigation technology (e.g., soil moisture and evapotranspiration sensors) to minimize runoff, conserve water and nutrients, and reduce pumping and associated energy costs. Additionally, minimizing water loss from surface reservoirs can be achieved by deepening reservoirs, covering surface water with shade balls, and constructing barriers to reduce wind speed. Adopting a comprehensive surface water and groundwater management plan entails redirecting excess water from surface water bodies to areas with aquifer outcrops to recharge the underlying aquifer systems. Lastly, enhancing local awareness among communities is crucial, focusing on both sustainable groundwater development and practices that can compromise the quality of available groundwater resources (Ahmed, 2020).

The sustainability of the NSAS represents a complex and pressing issue that requires concerted efforts from governments, stakeholders, and the international community to safeguard this vital resource and promote sustainable water management practices in the region. The consequences of depleting aquifers and contaminating groundwater often manifest over extended periods (Gleeson et al., 2012). Similarly, restoring a depleted aquifer and rectifying tainted groundwater may necessitate interventions spanning multiple generations. The establishment of groundwater sustainability objectives for numerous aquifers with a multigenerational outlook (spanning 50 to 100 years) is important, taking into account potential enduring repercussions (Gleeson et al., 2012). To delineate the timeframe for these sustainability objectives, it is recommended to consider the mean residence time, representing the duration required to attain a new equilibrium state. Mean residence times serve as valuable benchmarks for planning horizons due to their approximation of aquifer renewal periods. Specifically, the mean residence time of an aquifer, defined as the average duration for groundwater to traverse from recharge to discharge zones, offers insights into the temporal dimensions essential for framing sustainable goals (Gleeson et al., 2012). Ensuring the sustainability of the NSAS involves implementing a combination of conservation, management, and monitoring strategies. North Africa has been recognized as one of the highest susceptibility to diminishing groundwater reservoirs regions in the world (Kuper et al., 2018). Presently, it seems that the ongoing extraction pace is rendering groundwater an inadequate solution for addressing the prolonged impacts of climate fluctuations in the region (Kuper et al., 2018). Implementing integrated water management practices to ensure efficient use of water resources that include combining water demand management, conservation measures, and optimized irrigation techniques will assist in achieving sustainability for the NSAS over the next decades. Transboundary resource management involves the concept of judicious utilization of land and water resources. This necessitates taking into account the social and ecological aspects of groundwater usage, alongside the implementation of hydrological monitoring and modeling systems (King-Okumu & Abdelkhalek., 2021).

Although tackling the issue of excessive groundwater withdrawal stands out as a critical environmental and economic hurdle in the Middle East and Northern Africa MENA region, employing managed aquifer recharge techniques holds promise for enhancing agricultural water management in the regions where appropriate aquifers exist (Sherif et al., 2023). Groundwater replenishment, water banking, and artificial recharge represent intentional efforts to replenish aquifers for later retrieval or to yield environmental advantages (Sherif et al., 2023).

Summary and Conclusions

Groundwater serves as a lifeline for millions of people worldwide, particularly in arid and semi-arid regions where surface water sources are limited. It plays a vital role in providing domestic water, livestock, industry, and irrigation. However, several challenges threaten the sustainability of groundwater resources, including over-pumping, pollution, and climate change. The focus on NSAS in North Africa underscores the importance of transboundary aquifers in providing water security for multiple countries. While historical recharge processes have shaped the NSAS's characteristics, current extraction rates, and climate change projections pose significant threats to its long-term viability. Sustainable management practices and international cooperation are essential for preserving critical water sources for future generations.

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