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Climate Change and Its Impact on Groundwater Resources in Semi-Arid Regions: A Case Study of Libya

Nouraldin Almahdi Ibrahim Basha *
College of Arts and Sciences -Wadi Ataba, Fezzan university, Wadi Ataba, Libya
*Corresponding: Nou.basha@fezzanu.edu.ly

التغير المناخي وأثره على موارد المياه الجوفية في المناطق شبه القاحلة: دراسة حالة ليبيا

نورالدين المهدي إبراهيم باشا *
كلية الآداب والعلوم –وادي عتبة، جامعة فزان، وادي عتبة، ليبيا

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Abstract:
Libya is classified as a hyper-arid to semi-arid nation that relies almost entirely on non-renewable groundwater from the Nubian Sandstone Aquifer System (NSAS). This dependence is driven by extremely low annual rainfall, where 93% of the land receives less than 100 mm, and evaporation rates reach up to 4079 mm. Climate change is significantly accelerating resource depletion in the region. Projections indicate a temperature rise of 2 to 3 degrees Celsius by 2050, leading to a 10% to 15% increase in evapotranspiration. These climatic shifts result in unpredictable precipitation patterns and extended drought periods, which effectively prevent natural groundwater recharge in most regions. Currently, the Great Man-Made River (GMMR) project facilitates the extraction of 79% of Libya's water from these fossil sources. Agriculture remains the primary consumer, accounting for 83% of total water use, which has led to a critical decline in basin water levels by 1 to 2 meters annually. Furthermore, coastal aquifers face increasing risks of salinization and deteriorating water quality. This review, analyzing data from 2020 to 2025, identifies profound system vulnerabilities caused by the imbalance between supply and demand. To ensure long-term water security, the study proposes the implementation of Integrated Water Resources Management (IWRM) alongside the expansion of desalination, wastewater reuse systems, and advanced sustainability monitoring through technologies like GRACE. Without urgent adaptive strategies, the continued over-extraction of non-renewable resources under climate stress poses a severe threat to the nation's socio-economic stability.

Keywords: Climate Change, Groundwater Depletion, Semi-Arid Regions, Libya, Nubian Sandstone Aquifer, Recharge Reduction.

الملخص
تُصنف ليبيا كدولة شديدة الجفاف إلى شبه قاحلة تعتمد بشكل كامل تقريباً على المياه الجوفية غير المتجددة من نظام خزان الحجر الرملي النوبي (NSAS). ويعود هذا الاعتماد إلى انخفاض معدلات هطول الأمطار السنوية بشكل كبير، حيث تتلقى 93% من الأراضي أقل من 100 ملم، بينما تصل معدلات التبخر إلى 4079 ملم. ويؤدي التغير المناخي إلى تسريع استنزاف الموارد بشكل كبير في المنطقة. وتشير التوقعات إلى ارتفاع درجات الحرارة بمقدار 2 إلى 3 درجات مئوية بحلول عام 2050، مما يؤدي إلى زيادة بنسبة 10% إلى 15% في التبخر والنتح. وتؤدي هذه التحولات المناخية إلى أنماط هطول أمطار غير متوقعة وفترات جفاف ممتدة، مما يمنع فعلياً التغذية الطبيعية للمياه الجوفية في معظم المناطق. وفي الوقت الحالي،

يساهم مشروع النهر الصناعي العظيم في استخراج 79% من مياه ليبيا من هذه المصادر الأحفورية .ولا يزال قطاع الزراعة هو المستهلك الرئيسي، حيث يستحوذ على 83% من إجمالي استخدام المياه، مما أدى إلى انخفاض حاد في مستويات مياه الأحواض بمقدار 1 إلى 2 متر سنوياً .علاوة على ذلك، تواجه الخزانات الجوفية الساحلية مخاطر متزايدة من التملح وتدهور جودة المياه .وتحدد هذه المراجعة، التي حللت البيانات من 2020 إلى 2025، نقاط ضعف عميقة في النظام ناتجة عن عدم التوازن بين العرض والطلب .ولضمان الأمن المائي على المدى الطويل، تقترح الدراسة تنفيذ الإدارة المتكاملة للموارد المائية (IWRM) إلى جانب التوسع في تحلية المياه، وأنظمة إعادة استخدام مياه الصرف الصحي، ومراقبة الاستدامة المتقدمة من خلال تقنيات مثل (GRACE). وبدون استراتيجيات تكيف عاجلة، فإن الاستمرار في الإفراط في استخراج الموارد غير المتجددة تحت ضغط المناخ يشكل تهديداً خطيراً للاستقرار الاجتماعي والاقتصادي للبلاد.

الكلمات المفتاحية: التغير المناخي، استنزاف المياه الجوفية، المناطق شبه القاحلة، ليبيا، خزان الحجر الرملي النوبي، نقص التغذية المائية.

Introduction

Liberty is a land with an extremely arid to hyper-arid climate, and water scarcity is one of the most serious environmental and socio-economic problems of the country. Over 93 percent of the Libyan landmass receives less than 100 mm of rainfall in a year, and evaporation is higher than the rainfall parameter in the world by a great ratio. This has caused the virtual absence of surface water resources and renewable water availability is on a very low level. In such circumstances, the ground water forms the major and, in most cases, the only source of water that is available in domestic, farming and industrial applications. Relying on groundwater, especially on the fossil aquifers with a very low natural recharge rate, Libya is one of the most water-strained countries in the world.

Nubian Sandstone Aquifer System (NSAS) is the biggest and most important ground water source in Libya and North Africa in general. It is a transboundary fossil aquifer (Libya, Egypt, Sudan and Chad) that retains immense amounts of ground water that were deposited in the past climatic conditions when the area was wet. Nonetheless, the NSAS is practically non-renewable in human terms because the modern recharge in the existing arid climate conditions is very low. Such fossil aquifers have been significantly abstracted to support socio-economic development, large-scale irrigation, and urban water supply, although it has also led to serious concerns in terms of long-term sustainability, depletion, and deterioration of the water quality.

Climate change further complicates and puts more guesses into the management of the groundwater resources in arid and semi-arid areas. The Intergovernmental panel on climate change (IPCC) forecasts that global climate change would change the temperature regimes, precipitation, rates of evapotranspiration, and occurrence and severity of extreme climatic events such as droughts. These transformations have a direct and indirect impact on groundwater recharge, storage, flow dynamics as well as quality. Even the slightest changes in the climate variables can cause disproportionately huge consequences on the groundwater systems in the arid regions, such as Libya, due to their already delicate equilibrium between recharge and abstraction.

It has been proven in many studies that the potential evapotranspiration because of the high temperatures of climate change decreases the percentage of rainfall which can enter the subsurface and retain to recharge the groundwater. Increased evaporation does not only reduce recharge but also increases deficits of soil moisture, which reduces further infiltration processes. It has been repeatedly demonstrated through modeling in studies in various climatic regions that groundwater recharge is very sensitive to both temperature and precipitation, especially in semi-arid and arid areas with episodic recharge occurring and being dependent on infrequent periods of rainfall (Eckhardt and Ulbrich, 2003; Crosbie et al., 2010; Holman, 2006).

Besides temperature rise, climate change will raise variability in rainfall as opposed to the rainfall amount in most arid areas. Such change to more irregular and intense events of rainfall could decrease the effective recharge since the high-intensity storms tend to produce surface runoff and not infiltration, particularly in regions where soil permeability is small or land cover is destroyed. Such conditions can be very important in the management of recharge through preferential flow processes which are however hard to quantify and include appropriately in numerical groundwater models (Cuthbert and Tindimugaya, 2010; Moeck et al., 2016). As a result, the issue of uncertainty in recharge estimation is still considered one of the most important tasks in evaluating the effects of climate change on groundwater resources.

Groundwater modeling has taken critical part in interpreting as well as forecasting how aquifer systems will respond to climate variability/change. Numerical models enable the simulation of groundwater flow, recharge, and future conditions under the various conditions of different climatic conditions and abstraction. Numerical and conceptual groundwater models have identified the significance of climate projections and hydrogeological data in semi-arid areas to determine sustainability over the long term in groundwater (Abraham and Priyadarshini, 2021; Bohidar and Ahmad, 2021). Nevertheless, the specifics of the model, uncertainty in parameters, and availability of data may have a major effect on the simulation results, especially in those areas where there is scarce data, e.g., North Africa.

In addition to the quantity concerns, the climate change poses a high risk to the quality of the groundwater. Decreased recharge with concomitant increase in abstraction may cause dissolved solids to be concentrated, water salinized, and quality of water adversely affected particularly in coastal and dry inland aquifers. Modifications of groundwater flow regimes can as well increase the susceptibility of aquifers to anthropogenic contamination. There is a high number of investigations that use GIS-based evaluations, multivariate statistical tools, and water quality indicators that reveal that climate variability, land-use change, and water quality degradation have strong associations in semi-arid areas (Balamurugan and Kumar, 2016; Panneerselvam et al., 2020; Kumar, 2012).

Climate change has also further aggravated groundwater vulnerability in coastal aquifers because sea-level rise results in high potential of seawater intrusion. In the non-coastal arid areas, the process of falling groundwater level could cause upconing of more saline water, making ground water unusable in terms of drinking and irrigation. Through modeling and geospatial analysis, it has been noted that the recharge and groundwater levels change driven by climate change can lead to major changes in the distribution of salinity and a rise of health and agricultural risks (Dyer, 2014; Jayaraman and Chokkalingam, 2021b).

These findings around the world and the region are especially applicable to Libya. Climate change will increase in severity due to the over dependence of the country on the use of fossil groundwater, the high rate of population increase, agricultural development, and a lack of other water sources. The agricultural water demand would rise as crop water needs increase with the rise in temperatures and the urban demand would rise due to the influence of the population. Meanwhile, natural replenishment of aquifers is already very limited and its level is decreased by climate-induced losses of effective recharge and higher frequency of drought. Such supply demand imbalance endangers the sustainability of the water system based on groundwater in Libya.

Although groundwater is extremely vital in the water security of Libya, there has been limited comprehensive assessment that incorporates climate change effects, recharge processes of groundwater, and sustainability. Experiences of the international researches in arid and semi-arid areas offer useful methodological guidelines, such as numerical modeling, GIS-based multi-criteria analysis, and statistical methods of assessing the amount and quality of groundwater using changing climatic conditions (Fathi et al., 2021; Gaur et al., 2021; Pande and Moharir, 2021). In order to plan and develop water resources informatively and policy

making in the Libyan context, it is important to apply and modify these approaches to the situation.
The present study aims to add to existing research about climate change effects on groundwater resources through its investigation of Libya's desert environment and its use of fossil aquifers which include the NSAS. The research study will improve knowledge about climate change effects on groundwater resources and recharge processes and sustainability in Libya by using established modeling methods and climate impact assessment frameworks and groundwater quality assessment approaches that exist in scientific literature. The information obtained through this process will assist in creating adaptive groundwater management solutions which need to address existing water demands while ensuring long-term protection of resources in an area known for severe water shortages.

Literature Review

1. Climate Change and Groundwater Recharge.

The effects of climate change on groundwater recharge processes have been studied extensively with a lot of literature available to show that recharge is very sensitive to changes in temperature, precipitation, and evapotranspiration. Preliminary conceptual research showed that temperature rise and alteration of rain patterns can cause a significant decrease in effective groundwater recharge, especially in semi-arid and arid areas (Eckhardt and Ulbrich, 2003; Brouyere et al., 2003). These conclusions were supported by further reviews of the same carried out at the global and regional levels, noting that climate change typically results into lower recharge and greater unpredictability regarding the availability of groundwater (Holman, 2006; Dragoni and Sukhija, 2008; Green et al, 2011).
Recent researchers have developed recharge assessment by use of numerical and conceptual modeling. Abraham and Priyadarshini (2021) highlighted the significance of numerical groundwater modeling in estimating recharge in response to changing climatic conditions and especially in the semi-arid regions where recharge is intermittent and spatially heterogeneous. Similarly, it was shown by Bohidar and Ahmad (2021) that combined conceptual models and numerical flow simulation enhance the perception of the groundwater system response to climate variability.
Several modeling-based research studies ascertained that the projected climate change scenarios will tend to increase the shortages of recharges. As Ghazavi and Ebrahimi (2018) demonstrated, the future climatic conditions in arid conditions greatly decrease the rate of ground water recharge, primarily because of the elevated level of evapotranspiration and the infiltration rate. Similar conclusions were drawn in watershed-based investigations of various climatic zones meaning that the tendency to decrease recharge in climate change is generally similar in the world (Jyrkama and Sykes, 2007; Meixner et al., 2016; Wu et al., 2020).

2. Preferential Flow, Model Structure and Uncertainty.

The recharge estimation is still a significant issue of uncertainty in the study of impacts of climate change. In his article, Holman (2006) indicated the weakness in recharge modeling, especially in regard to the uncertainty of parameters and model structure. Subsequent research also established that the conceptualization of models and spatial resolution are important factors in estimating groundwater recharge (Moeck et al., 2016).
Preferential flow processes are also known as one of the main processes that govern recharge in arid and semi-arid areas. Cuthbert and Tindimugaya (2010) stressed that failure to have preferential flow pathways may result into a great underestimation or overestimation of recharge, particularly, when assessing the effects of climate change. The findings propose that the recharge forecasts of the fossil aquifer systems must be viewed with a lot of caution, especially in the climate conditions in the future.

3. **Effects of climate change on ground water levels and availability.**

A lot of research has been conducted on the impacts of climate change on the levels of ground water and its long-term availability. The regional modeling work revealed that a change in recharge regimes causes a decrease in the groundwater and an increase in seasonality (Crosbie et al., 2010; Rivard et al., 2014). Luoma and Okkonen (2014) also demonstrated that climate change and sea-level rise can exert combined effects that affect the groundwater and surface leakage particularly in coastal aquifers.

On the international level, Earman and Dettinger (2011) and Moseki (2017) found that the effects of climate change on groundwater are largely adverse in water-strained areas, which exacerbates the existing water stress. The recent high-impact research confirmed divergent regional responses but pointed towards the fact that arid and semi-arid aquifers are one of the most vulnerable systems globally (Wu et al., 2020).

4. **Quality of Groundwater, Climate Stress and Anthropogenic Influence.**

Besides the issue of quantity, we have extensively recorded degradation of groundwater quality by both climatic and anthropogenic forces. Multivariate statistical and GIS-based analyses have revealed that groundwater chemistry depends greatly on climate changes, land-use alteration, and intensive abstraction of groundwater (Balamurugan and Balakumaran, 2015; Balamurugan and Kumar, 2016).

Numerous studies on semi-arid areas in India proved that the drinking and irrigation water quality in these areas is becoming very vulnerable to both natural and man-made factors. These research papers used GIS, water quality indices, and health risk assessment models to assess the suitability of groundwater (Balamurugan et al., 2020; Panneerselvam et al., 2020; Ravi et al., 2020). It was discovered that climate-induced decreases in recharge exacerbated salinity and contaminant levels, and this aggravated health and agricultural hazards (Balamurugan et al., 2020b; Panneerselvam et al., 2021b).

The latest developments are the use of artificial intelligence and machine learning to forecast parameters of groundwater quality in dynamic environments. Kouadri et al. (2022) have shown that ANN and LSTM models can be used as powerful predictive tools to predict the quality of groundwater in semi-arid areas, which can be a useful addition to adaptive groundwater management.

5. **GIS, Remote Sensing and Decision Support on Groundwater Studies.**

Geospatial methods have also been recognized as a key instrument in groundwater evaluation and especially where data are scarce in semi-arid areas. Some articles emphasized the usefulness of multi-criteria decision analysis (MCDA) based on GIS in groundwater recharge, vulnerability, and a planned aquifer recharge (Fathi et al., 2021; Rajesh et al., 2021).

The application of remote sensing has also been huge to examine land-use and land-cover alteration and its effect on the ground water systems. Pande et al. (2018, 2021) showed that the land-use alteration can have a considerable effect on the hydrology, which affects the level of recharge and groundwater sustainability. Such results are especially important to arid regions where land degradation and agricultural growth increase stresses produced by climate.

6. **Consequences to Fossil Aquifers and Semi-Arid Regions.**

The literature review has shown that in semi-arid and arid areas, the fossil aquifers are compounded in risks due to climate change and intensive groundwater abstraction. Even though these aquifers are less vulnerable to temporary changes in climatic conditions, the long-term changes in climate decrease the already low recharge and make people more reliant on the non-renewable groundwater reserves (Kumar, 2012; Kumar, 2016).

Research on issues related to groundwater management highlights the importance of integrated planning systems incorporating the use of numerical modeling, the geospatial analysis system, and sophisticated statistical solutions to provide sustainability in the face of climate uncertainty (Priyan, 2021; Shah, 2013). These lessons offer a powerful theoretical and methodological basis to the evaluation of groundwater sustainability in dry areas that depend on the fossil aquifer systems.

7. **Synthesis and Research Gap**

In general, past research establishes that climate change is likely to lower the groundwater recharge, augment groundwater sinking, and aggravate the worsening of water quality, especially in semi-arid and dry areas. Although much progress has been achieved on the modeling front, GIS-driven analysis and predictive models, a gap in specific characterization of the region-based analysis on fossil aquifer systems in combined climate and abstraction pressure has been identified. It is in this light that specific research is required to implement climate predictions, recharge processes, and groundwater sustainability in areas with a high-water demand, like North Africa.

Methodology

In this paper, a systematic literature review is utilized as the dominant methodological strategy, which is aimed to synthesize the latest and most topical research (20202025) on the dynamics of groundwater in Libya specifically in the Nubian Sandstone Aquifer System (NSAS) and the effects of climatic variability and change. The literature review technique was chosen due to the possibility of the full study of existing empirical data, models, and observation of data in a variety of fields such as hydrogeology, remote sensing, climate science, and water resource management without necessarily collecting new field data because it is often limited by logistical and geopolitical factors in the area.

The review process will include formulating a structured search strategy, i.e. the selection of key themes of interest: groundwater extraction and depletion in Libya/NSAS, climate change and recharge processes, satellite-based gravimetric measurements (e.g. GRACE/GRACE-FO), and hydrogeological models. Relevant search terms were integrated and narrowed down through repetitions to ensure that both broad and narrow topics were covered such as the following: "NSAS, groundwater recharge Libya, GRACE groundwater storage, climate effects in arid aquifers, and the use of hydrogeological numerical models. Major academic databases and repositories, such as Scopus, Web of Science, and Google Scholar were searchable, and institutional and agency reports on development agencies (e.g., UNICEF, World Bank) that covered water resource trends in Libya and North Africa have been searched.

To guarantee the recency and relevance of evidence base, the screening criteria focused on peer-reviewed journal articles, book chapters and technical reports published in the period between 2020 and 2025. Earlier, albeit classic, articles were also used selectively where they offered analytical theoretical foundation or methodological background (e.g., classical modeling methods and recharge estimation procedures). All of the retrieved sources were evaluated on their quality criteria in terms of their relevance to the research questions, methodology, and the applicability of geographical scope to Libya/NSAS or similar arid aquifer systems.

The information mined in the literature review consisted of both quantitative (e.g., extraction volumes, recharge estimates, GRACE-anomalies of storage) and qualitative data (e.g., model interpretations, vulnerability analyses, policy implications). The data were structured into thematic matrices to support a qualitative narrative synthesis, showing the convergences and divergences in the results, methodology, and outcomes of projections. Statistical tendencies and model predictions were interpreted relative to each other to create a unified attitude of NSAS action amidst concerted climate and anthropogenic tension.

Transparency and replicability served as the principles of the synthesis phase, and even in cases where gaps or inconsistencies in the literature were discovered, it was clearly stated that such factors were the guidelines to be followed in future research. This approach will provide a strong and evidence-based case to explain the dynamics surrounding the complex nature of groundwater resources in Libya and other arid environments by developing a robust approach to conducting systematic search processes as well as thematic analysis.

Results and Discussion

The section presents key quantitative and qualitative results which show how water scarcity and climate stress and groundwater depletion affect Libya while examining the Nubian Sandstone Aquifer System (NSAS) as the primary case study. The section starts with thematic tables which present data from 2020 to 2025 and continues with a discussion that analyzes climate indicators and groundwater extraction patterns and their effects on sustainability.

Climate and Water Scarcity Indicators in Libya

Table (1) Key Climate and Water Statistics for Libya (Recent Data).

Parameter	Value / Estimate	Source / Notes (2020–2025)
Average Annual Rainfall	< 56 mm (93% of land < 100 mm)	UNICEF (2022); World Bank Climate Profile
Annual Evaporation Rate	> 3000–4079 mm	Various studies; highest in coastal and western regions
Per Capita Freshwater Availability	< 200 m^3/year	UNICEF (2022); absolute scarcity threshold < 500 m^3
Groundwater Extraction (Total)	79% unsustainable (non-renewable)	UNICEF (2022)
Agricultural Water Use	83% of total freshwater use	UNICEF (2022)
Projected Temperature Rise	+2 to +3 °C by 2050	Regional climate projections
Evapotranspiration Increase	+10–15% due to warming	Climate model projections

Table 1 displays the extreme dry climate conditions and complete lack of water resources which exist in Libya. The country experiences its lowest annual rainfall levels because more than 90% of its territory receives less than 100 mm of rain each year which makes Libya one of the most water-scarce countries worldwide. The annual evaporation rates exceed 3000 mm in most areas while specific regions experience evaporation levels that surpass 4000 mm which creates a substantial water deficit. The water imbalance practically prevents any significant surface water storage capacity while it dramatically restricts natural groundwater recharge processes.

The absolute water scarcity situation occurs when per capita freshwater availability drops below 200 m^3/year, which stands far below the international benchmark of 500 m^3/year. The overall water scarcity problem worsens because agriculture accounts for nearly 83% of all freshwater usage across different sectors. The agricultural sector relies heavily on water-intensive farming methods which leads to quick groundwater depletion in the arid region.

The climate projections create additional challenges for the existing problems. The expected temperature rises of 2–3 °C between now and mid-century will boost evapotranspiration rates by 10–15% which will decrease effective recharge capacity even further. The research demonstrates that Libya faces a water crisis because of two main factors, which include excessive water extraction and the ongoing negative effects of climate change.

Characteristics and Depletion Trends of the Nubian Sandstone Aquifer System (NSAS)

Table (2) Nubian Sandstone Aquifer System (NSAS): Key Parameters (Focus on Libya)

Parameter	Estimate (Libya / NSAS)	Notes / Source
Total NSAS Water Volume	~150,000 km^3	Fossil, largely non-renewable
Recharge Rate (Local / Modern)	< 5–10 mm/year	Minimal in Libya; episodic recharge only
Libya Extraction Rate	~0.85 km^3/year	Recent estimates; GMMR is dominant user
Depletion Rate (Key Basins)	1–2 m/year decline	Observed since 1980s
Projected Withdrawals (2100)	Significant increase (e.g., +0.22 km^3 in scenarios)	Population-driven models
GRACE Storage Loss (Regional)	~50 km^3 (2003–2016); ongoing	GRACE-based North African studies

The research findings presented in Table 2 demonstrate that the NSAS aquifer system which exists in Libya functions as a nonrenewable resource because current water extraction activities exceed all operational limits. The aquifer contains a vast water reservoir which scientists estimate to reach 150000 cubic kilometers but they identify most of this water as fossil resources which formed during ancient rainy periods. Libyan regions experience extremely low recharge rates which stay under 5 to 10 millimeters annually and only happen during exceptional rainfall occurrences.

The current extraction rate of 0.85 cubic kilometers per year in Libya represents an ongoing and substantial reduction of this fossil resource which the Great Man-Made River GMMR project drives. Groundwater levels show a yearly decrease between 1 and 2 meters for major basins including Kufra and Sarir based on monitoring data which has existed since the 1980s. The satellite gravimetry system from GRACE confirms the research results by showing that North African transboundary aquifers experienced regional groundwater storage reductions of about 50 cubic kilometers between 2003 and 2016 which continued to decrease after that period. The model predictions demonstrate that water withdrawals will experience substantial growth until the year 2100 because of both population expansion and development activities which create critical challenges for maintaining intergenerational fairness and securing water resources.

Water Use, Structure, and Sustainability Challenges

Table (3) Water Use and Sustainability Challenges in Libya

Sector	% Of Total Water Use	Impact of Climate Change and Depletion
Agriculture	~83%	Highly vulnerable; declining yields due to recharge reduction
Domestic / Urban	~10–15%	Salinization in coastal aquifers; quality deterioration
Industrial	Minor share	Increasing demand with urban growth
Overall Sustainability	Unsustainable	~79% of extraction from non-renewable sources

The water usage pattern in Libya demonstrates extreme agricultural preference which constitutes 90 percent of total water consumption. Agricultural activities experience intense climate impacts and groundwater depletion problems which make them vulnerable to climate change. The agricultural sector faces two main challenges which reduce its productivity. The aquifer system faces increasing pressure because water extraction activities continue without interruption.

The smaller water consumption used by cities and households in northern Libya faces increasing danger from both coastal salinization and the decline of groundwater resources. Industrial water needs remain minimal at present but will increase as cities expand which will create additional water resource demands on already depleted systems.

The study found that 79 percent of Libya's groundwater extraction activities operate at unsustainable levels. The situation demands urgent action to control water usage while improving operational efficiency and developing new water supply methods.

Integrated Interpretation

The combined results from climate indicators, aquifer parameters, and sectoral water use show a consistent pattern which demonstrates that water sources receive minimal recharge while human activities extract increasing amounts of water throughout the climate change period. Libya achieves short- to medium-term water security through its NSAS water resources yet this practice creates long-term sustainability problems.

The rising temperatures together with decreasing recharge and growing population demand will lead to groundwater depletion and water quality decline and increased economic and social vulnerability unless major policies are implemented.

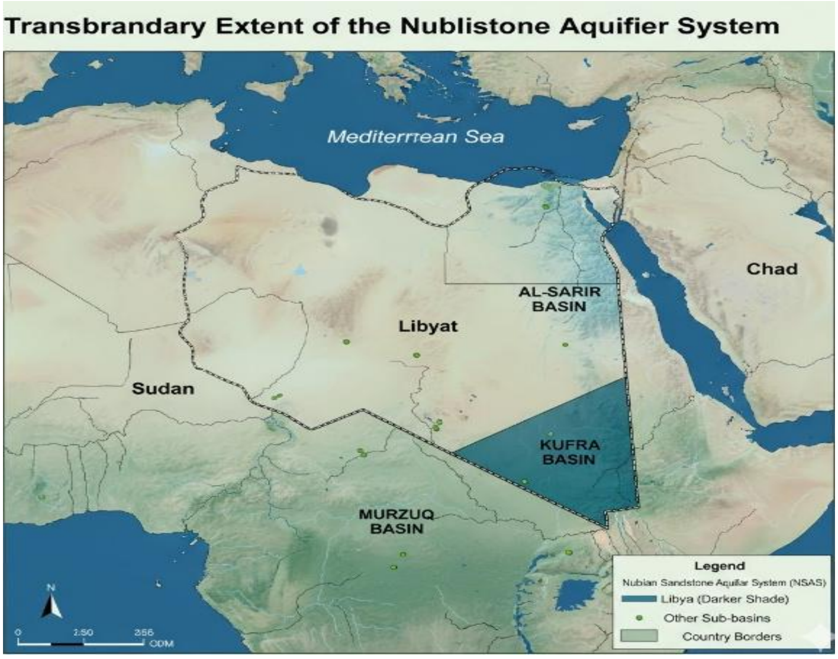

Figure (1) NSAS Extent Map.

This figure shows how the Nubian Sandstone Aquifer System (NSAS) reaches beyond national borders to cover Libya, Egypt, Sudan, and Chad. The map shows that Libya controls a large area of the aquifer because it displays the main sub-basin areas which include Kufra, Sarir, and Murzuq. The figure shows that the aquifer exists as a shared resource between multiple countries which need to work together to manage their groundwater resources. The need for this cooperation exists because Libya depends on the NSAS for its main source of freshwater.

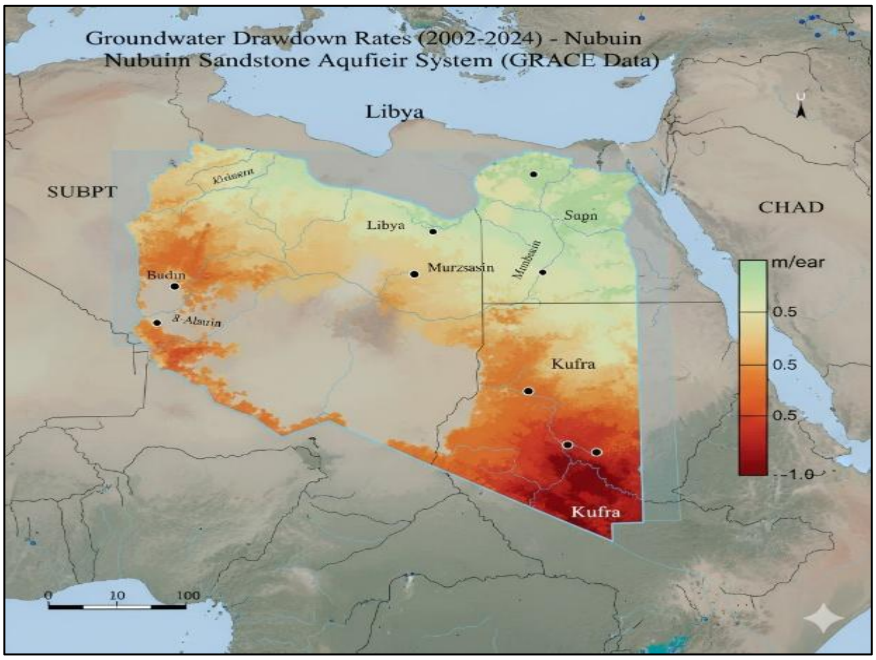

Figure (2) Groundwater Depletion Map.

The figure shows groundwater depletion patterns throughout the NSAS area which uses color-coded drawdown rates to show areas with significant groundwater level decline. The Kufra region of Southern Libyan basins functions as the primary area for groundwater depletion. The visualization verifies GRACE satellite assessment results because it shows the long-term effects of groundwater abstraction that exceeds natural recharge which confirms the non-renewable use of fossil groundwater resources.

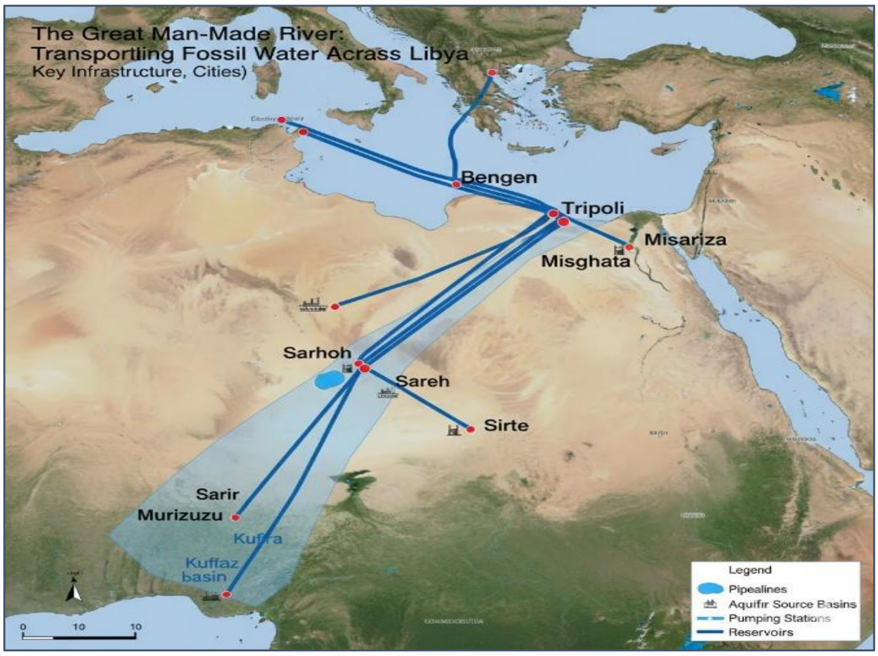

Figure (3) Great Man-Made River (GMMR)

The Great Man-Made River (GMMR) project distribution system shows its main pipelines which deliver groundwater from desert aquifers in the southern region to northern coastal cities that have high population density. The GGGMR system shows its strategic value and operational capacity to deliver water for domestic and agricultural needs while the system needs ongoing NSAS water extraction to maintain operations which creates sustainability issues.

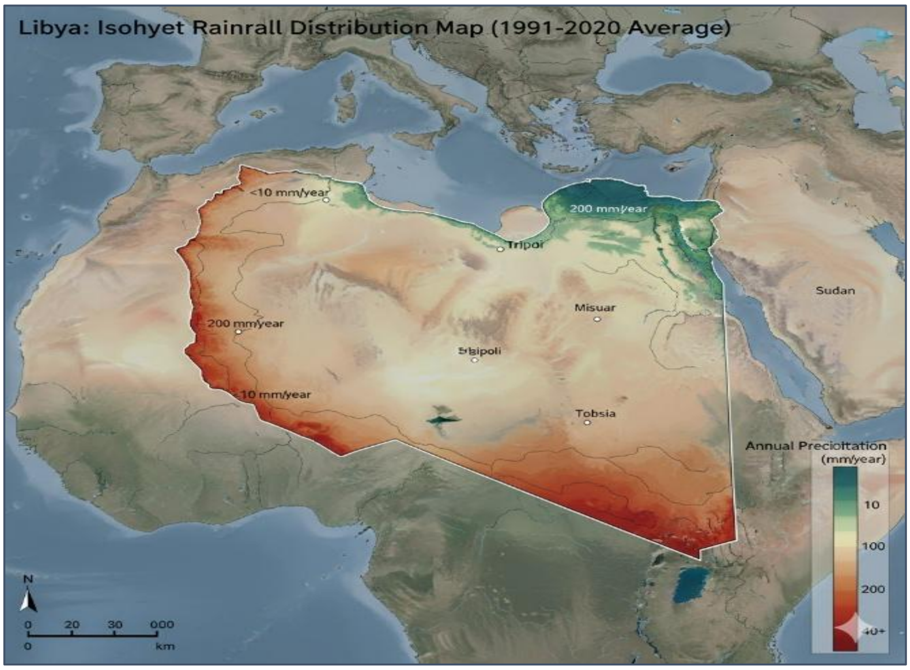

Figure (4) Libya Rainfall Distribution.

The figure shows how average annual rainfall patterns distribute across Libya through the use of isohyet contours. The map shows that northern coastal areas receive more rainfall than central and southern Libya, which experiences extreme drought conditions because of its low precipitation levels. The figure demonstrates how natural groundwater recharge capacity in Libya remains restricted while showing how the country depends on fossil aquifers for water supply during present and future climate scenarios.

Conclusion

Libya's groundwater crisis in its semi-arid and hyper-arid regions experiences worsening effects from climate change because it reduces recharge rates while increasing evaporation and extending drought periods for NSAS water sources. The process of over-extraction through GMMR results in rapid resource depletion at a rate between 1 and 2 meters per year which causes salinization and quality problems. The latest data from 2020 to 2025 show unsustainable patterns because agriculture consumes most of the available resources. The urgent need for adaptation requires IWRM implementation while expanding desalination and wastewater reuse programs and developing efficient irrigation systems and satellite monitoring through GRACE technology. Transboundary NSAS cooperation needs to establish climate resilience as a core requirement. The lack of action will create major risks for water security and food production and livelihoods; however, sustainable strategies enable resource conservation during times of resource decline.

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