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Water Scarcity Review; Challenges and Future Prospects, A Case Study in Egypt

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ABSTRACT
A major global challenge is ensuring access to clean drinking water as freshwater resources become increasingly scarce. This review presented an overview of the causes, types, aspects, future challenges, and potential solutions to water scarcity, using Egypt as a case study. It highlighted Egypt's current water situation, the factors contributing to scarcity, and the types of water resources available in the country. Several measures implemented by Egypt to mitigate water scarcity risks and manage water resources were also discussed. Improving river water quality forecasting is essential to support sustainable water management strategies. Brackish and seawater desalination represent promising options to alleviate scarcity; however, these technologies remain constrained by high costs, intensive energy requirements, and the environmental impacts of hypersaline effluents. The insights from this review provide valuable guidance for researchers, policymakers, and practitioners working to safeguard water resources globally.

1. Water resources

Water is a fundamental element of human existence, and its conservation is vital for sustaining a healthy environment for all living organisms. Although water covers over 71% of the Earth's surface, approximately 96% of it is saline and confined to the oceans, while only 3% is freshwater. Despite this abundance, potable water remains scarce due to factors such as population growth, economic expansion, and pollution. In response, the United Nations established a set of goals that include eliminating water pollution sources, protecting river ecosystems, and strengthening international cooperation **(SDG Report, 2024)**.

Regrettably, global freshwater resources are under severe strain. Rapid population growth, coupled with increased urbanization, has led to excessive water use that exceeds natural replenishment rates. Urban expansion has also reduced groundwater recharge because of the proliferation of impermeable surfaces. In addition, freshwater systems face pollution pressures from industrial, residential, and agricultural activities **(Salehi, 2022)**. The United Nations warns that while global populations continue to rise, freshwater availability is diminishing, with many countries expected to face severe scarcity in the coming years. In developing nations, this challenge is intensified by mismanagement, climate change, agricultural demands, population pressures, and limited financial and technical resources **(Jones *et al.*, 2024)**.

The water cycle is essential for life on Earth, as it regulates climate, sustains ecosystems, and influences weather systems. Through its circulation, water redistributes heat across the globe, shaping climate and weather patterns (Fig. 1). Moreover, the water cycle plays a critical role in replenishing freshwater reserves, which are indispensable for drinking, agriculture, and industrial use **(Liu *et al.*, 2021)**.

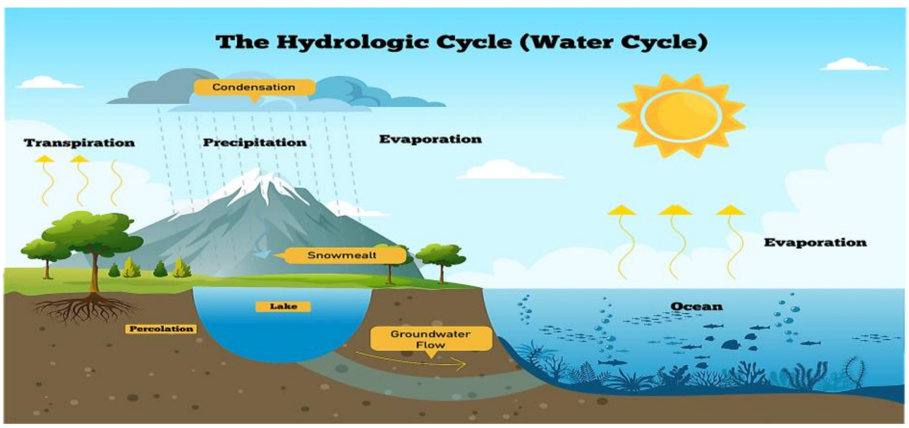

Fig. 1. The water cycle

Water is utilized across various domains. Domestic applications account for 11% of water usage for drinking, bathing, cooking, and cleansing dishes, clothing, vegetables, and numerous other functions. Potable water refers to water that is suitable for drinking. Agriculture accounts for about 70% of global water consumption **(Narmilan *et al*., 2020)**. Water is employed for consumption, household purposes, and agriculture production for public health **(Kumar *et al*., 2024)**. It is essential to preserve water quality balance. The escalating need for enhanced comfort has resulted in the decline of air quality, the destruction of landscapes, and the pollution of water resources. This trend has highlighted the necessity for a comprehensive analysis, assessment, and restoration of what was once unblemished. As a result, the acknowledgement of the significance of evaluating water quality arose in the 1960s, leading to the enactment of laws aimed at mitigating the deterioration of natural water resources' purity **(Qu & Peng, 2025)**. Water reservoirs are primarily categorized into two types: surface water reservoirs (including rivers, lakes, reservoirs, and coastal regions) and groundwater reservoirs (comprising infiltration galleries and springs) **(Yang *et al*., 2020)**.

2. Water scarcity

Water scarcity occurs when the available water supply is insufficient to meet demand in a region. Addressing this issue requires early interventions to curb freshwater demand and limit groundwater exploitation. As Eliot (1965) stated, *"Drought is the death of the earth."* Climate change and the demand for bioenergy further exacerbate the complex dynamics between water availability and global development **(Stahl & King, 2020)**.

2.1. Types of water scarcity

- **Physical water scarcity**: Also called absolute scarcity, this refers to the lack of water resources in a given region. The FAO estimates that more than 1.2 billion people live in arid or semi-arid regions experiencing physical water scarcity. This condition is often seasonal, with two-thirds of the global population living in areas where water shortages occur for at least one month each year. Population growth and unpredictable climate patterns are expected to worsen this scarcity.
- **Economic water scarcity**: This occurs when inadequate infrastructure, sanitation, recycling, and water treatment prevent populations from accessing sufficient water, even if resources exist **(Salehi, 2022)**.

2.2. Causes of water scarcity

The Middle East and North Africa (MENA) are among the most vulnerable regions. In Europe, 50% of countries also face seasonal or periodic water stress. Major causes include population growth, urbanization, climate change, pollution, and unsustainable agriculture **(Boloorani *et al.*, 2024; UN, 2013)**:

a. **Inadequate governance** – Weak institutional frameworks, inequitable allocation, and poor enforcement mechanisms result in inefficient water management **(Salehi, 2022)**.

b. **Over-exploitation** – Agriculture, industry, and households often consume water at unsustainable rates, with agriculture alone responsible for over 70% of water withdrawals, much of it wasted due to inefficient irrigation.

c. **Pollution** – Untreated sewage, industrial effluents, and agricultural runoff contaminate freshwater, rendering it unsafe for use. Heavy metals, pathogens, herbicides, and other pollutants pose significant risks to public health and ecosystems **(Khedr & Ghannam, 2025)**.

d. **Population growth** – Expanding populations increase demand for drinking water, sanitation, agriculture, and industry, often outpacing infrastructure development.

e. **Ecosystem degradation** – Deforestation, land use changes, and basin modifications reduce ecosystems' ability to regulate and retain water, thereby disrupting hydrological cycles and increasing vulnerability to climate change **(William & Scott, 2014)**.

2.3. Aspects of water scarcity

- **Quantitative dimensions**: These relate to the volume of water resources available, which fluctuate seasonally and geographically. Over-consumption, mismanagement, and inequitable distribution exacerbate shortages. Globally, around 783 million people lack access to potable water **(Barkdull & Harris, 2019)**.
- **Qualitative dimensions**: These occur when water is available but contaminated, rendering it unfit for use. Pollution from microbial, chemical, and physical sources—including fertilizers, industrial waste, and thermal pollution—contributes to this problem. Point sources (e.g., industrial discharges) are easier to regulate than diffuse sources (e.g., agricultural runoff), which remain a major challenge despite modern treatment facilities **(Barrucand *et al.*, 2017; Khedr & Ali, 2024; Khedr *et al.*, 2024)**.

3. Case study: Water scarcity in Egypt

3.1. Current water situation

Africa is home to several major rivers and lakes, including the Nile, Congo, Zambezi, Niger, and Lake Victoria. However, water scarcity in many African nations is driven by fiscal and governance challenges. Egypt, in particular, faces chronic scarcity, exacerbated by rapid population growth and limited financial resources **(Jahin *et al.*, 2023)**. In 2015, per capita freshwater availability in most countries fell below 1000m^3 per year, well under the global average. Egypt relies heavily on external water sources, with about 98% of its renewable freshwater originating outside its borders, primarily from the Nile River and groundwater basins. The Nile alone supplies nearly 90% of the country's needs, making it central to Egyptian water policy and management strategies.

3.2. Types of water resources in Egypt

Egypt's water resources include surface water, shallow groundwater, limited rainfall, and non-traditional sources such as agricultural drainage reuse, wastewater recycling, rainwater harvesting, and desalination **(Ferrari *et al.*, 2014; SIS, 2017)**.

3.2.1. Surface water

Egypt contains several basins and lakes **(Donia & Negm, 2018; Fouad, 2023)**:

- **Middle Nile Basin**: 326,751 km^2 (33% of the country), extending from north to south.
- **North Interior Basin**: 520,881 km^2 (52%), including the Qattara Depression.
- **Mediterranean Coastal Basin**: 65,568 km^2 (6%).
- **Northeast Coast Basin**: 88,250 km^2 (8%), a narrow strip along the Red Sea.

- **Lakes**: Egypt has around 12 major lakes, including:
    - **Deltaic lakes**: Mariout, Edku, Burullus, and Manzala
    - **Non-deltaic lake**: Bardawil (northern Sinai)
    - **Others**: Lake Nasser (High Dam), Toshka Lakes, Lake Qarun (Morris Lake), Wadi El Natrun Lakes, Wadi El Rayan Lakes (Fayoum), Lake Timsah, Great Bitter Lakes (Ismailia), and the salt lakes of Siwa.

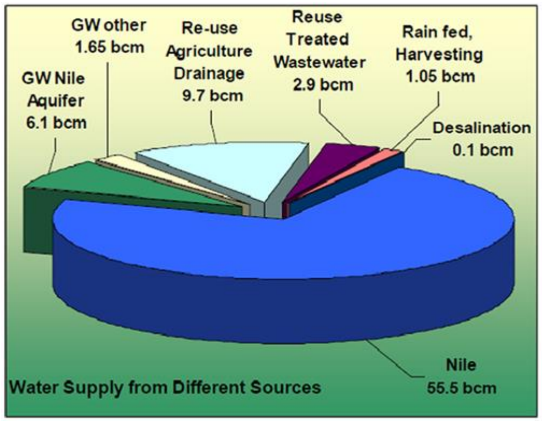

Fig. 2. Water Sources in Egypt. The groundwater sourced from the western desert yields 1.65 * 10^9 m^3/year, but municipal wastewater reuse amounts to approximately 2.9 * 10^9 m^3/year, and the projected reuse capacity of agricultural wastewater in the Nile Valley and Delta is 9.7 * 10^9 m^3/ year **(Elsaie *et al*., 2023)**

3.2.2 The River Nile

The Nile is Egypt's principal waterway and one of the most significant rivers in the world. Measuring approximately 6.6 × 10^3 km (about 6,700 km), it ranks as the second longest river globally, traversing from South to North across the 3.4 × 10^6 km^2 Nile River Basin (NRB) **(Ahmed *et al.*, 2024)** (Fig. 3).

The Nile has two main tributaries:

- **The White Nile**, ~3.7 × 10^3 km in length, originates from Lake Victoria and flows through Uganda and Sudan.
- **The Blue Nile**, ~1.5 × 10^3 km in length, begins at Lake Tana in Ethiopia before joining the White Nile in Sudan.

The confluence of these rivers forms the main Nile, which flows northward through Egypt and empties into the Mediterranean Sea. The Blue Nile is particularly important for agriculture and hydropower generation in Sudan and Egypt, supplying ~95% of the sediment to the NRB **(Ahmed *et al.*, 2024)**.

The NRB extends across 35° of latitude—from 4° south (near Lake Tanganyika) to 31° north of the equator—and spans over nine longitudes, from 29° in the equatorial plateau to 38° at its Abyssinian sources. Covering ~2.9 million km², the basin stretches across 10 African nations: Ethiopia, Eritrea, Uganda, Burundi, Tanzania, Rwanda, Sudan, Democratic Republic of Congo, Kenya, and Egypt. Together, these countries occupy ~0.7 million km² within the basin.

Climatically, the river traverses diverse zones—from equatorial regions with ~800 mm annual rainfall to the arid deserts of northern Sudan and southern Egypt. Annual Nile flow varies considerably: from a minimum of ~42 BCM/yr to a maximum of ~150 BCM/yr recorded at Aswan, with a long-term average of ~84 BCM/yr. The Nile collects water from three main basins: the Ethiopian Plateau, the Tropical Lakes Plateau, and Bahr El Ghazal.

For Egypt, the Nile provides ~90% of total renewable freshwater supplies—amounting to 55.5 BCM/yr under the 1959 Nile Waters Agreement with Sudan. Most of this allocation supports irrigated agriculture in the Nile Valley and Delta. However, evaporation from Lake Nasser (the Aswan High Dam reservoir) results in losses of ~10 BCM/yr.

Reservoir infrastructure further regulates Nile waters. In Sudan, the Roseires and Merowe reservoirs (constructed in 1966 and 2009, with capacities of 7.4km³ each) lie ~100km and ~900km downstream of the Grand Ethiopian Renaissance Dam (GERD), respectively. In Egypt, Lake Nasser holds an estimated 132km³ of water, while the Toshka basin serves as an auxiliary reservoir. When Lake Nasser's water level exceeds ~180m above sea level, surplus water is diverted into Toshka **(Bastawesy *et al.*, 2008)**.

3.2.3 Groundwater

Egypt also possesses substantial groundwater reserves, though many remain underutilized. The total volume is estimated at ~40,000 BCM **(Abdelhafez *et al.*, 2020)**. Challenges to exploitation include the extreme depth of aquifers—reaching up to 1,500 m in some areas—and deteriorating water quality with depth.

Renewable groundwater is concentrated in the Nile Valley (~200 BCM) and the Delta (~400 BCM). These reserves are hydrologically connected to the Nile system. Since 2006, annual withdrawals have averaged ~6.5 BCM, a level considered within the safe extraction threshold of ~7.5 BCM/yr, as defined by the Groundwater Research Institute **(Roshdy *et al.*, 2025)**.

Fig. 3. The Nile River Basin and its drainage network

The Nubian Sandstone Aquifer System, extending across northeastern Africa (Egypt, Sudan, Libya, and Chad), is believed to contain over 40 trillion m³ of groundwater **(Al-Gamal, 2020)**. Although this reservoir represents an important potential source, Egypt cannot fully utilize it due to the extreme depths—reaching up to 1,500m in some areas. Withdrawals are estimated at ~0.6 billion m³ annually, enough to irrigate approximately 63,300 hectares in the Owainat region **(Abdelhafez *et al.*, 2020)**.

3.2.4. Rainfall and floods

Egypt is predominantly arid, except for its northern coastal areas. Annual rainfall ranges between 50–150 mm along the northeastern coast, allowing limited cultivation of ~42,000 hectares. Precipitation increases eastward, reaching ~150 mm in El-Arish and ~250 mm in Rafah **(Abdelhafez *et al.*, 2020)**.

In the northern regions of Egypt (covering ~200,000 km²), typical winter precipitation contributes between 5–10 billion m³ of water annually. Of this volume, ~1.5–3 billion m³ becomes surface runoff, while the remainder either evaporates, transpires, or infiltrates to recharge groundwater aquifers **(Abdelhafez *et al.*, 2020)**.

3.2.5. Desalinated water

With over 2,400km of coastline along the Red Sea and Mediterranean, and extensive brackish aquifers, desalination has emerged as a renewable water resource for Egypt. Historically, the country adopted distillation, then electrodialysis (ED), and most recently reverse osmosis (RO) technologies **(Khedr, 2016)**.

Currently, Egypt promotes desalination in both public and private sectors. Advances in global desalination technologies have reduced costs, making seawater desalination more competitive **(Abdelhafez *et al.*, 2020)**. As of recent reports, 81 desalination plants operate in governorates such as North Sinai, South Sinai, Red Sea, Matruh, Ismailia, and Suez, with a combined capacity of 913,690m³/ day (Table 1). Eleven more plants, totaling 465,103m³/ day, are under development in Matruh, North Sinai, South Sinai, Port Said, and Dakahlia (Table 2).

Notable large-scale plants include El Alamein and El Galala, each with capacities of 150,000 m³/day, while some of the most significant installations are located in East Port Said (Fig. 4).

3.2.6. Wastewater reuse

Treated wastewater has become an increasingly important supplementary water source for irrigation, provided it meets health standards. Egypt currently collects over 5 billion m³ of wastewater annually, with strategic plans to reuse ~4.5 billion m³. Treated wastewater volumes have grown steadily—from 0.26 billion m³/year in the early 1990s, to 0.6 billion m³/year by the 2000s, and reaching ~4 billion m³/year since 2017 **(Abdelhafez *et al.*, 2020)**.

Most treated wastewater is used to irrigate non-food crops, afforest arid lands, and support timber production.

3.2.7. Agricultural drainage water reuse

Agricultural drainage water, originating from irrigation return flows and soil leaching, represents another significant resource. However, this water is often mixed with runoff contaminated by agrochemicals and industrial effluents. Its salinity ranges from 700– 3000mg/ L, making it unsuitable for many crops without treatment **(Attia, 2018)**.

To reduce risks, direct treatment of sub-drains and main drains is required before mixing with freshwater. Moreover, discharging at least 50% of total drainage water into the sea is critical for maintaining the salinity balance of the Nile Delta and preventing seawater intrusion into the North Delta aquifer.

Table 1. The distribution of existing desalination plants in the governorates **(Elsaie *et al*., 2023)**

Governorate	Matrouh	Red Sea	North Sinai	South Sinai	Ismailia	Suez	Total
No. of desalination plants	18	17	29	14	1	2	81
Design capacity (m^3/day)	302,500	109,700	52,090	161,000	2400	286,000	913,690

Table 2. The desalination plants being under construction in the governorates **(Elsaie *et al*., 2023)**

Governorate	No. of desalination plants	Design capacity
Matrouh	East Matrouh	65,000
Port Said	West Port Said	20,000
	East Port Said	150,000
North Sinai	El-Arish & Sheikh Zueid cities	100,000
South Sinai	Nabq Phase Two	6,000
Suez	Ain Sukhna Expansions	70,000
Alexandria	Marbella	2,000
Dakahlia	New Mansoura	40,000
Red Sea	El Shalateen Expansions	6,000
	Abu Ramad Expansions	3,000
	Halayeb Expansions	3,000

3.2.8 Artificial groundwater recharge

Flash floods in Egypt, particularly in the Eastern Desert and Sinai, present a considerable opportunity for floodwater harvesting. Such practices can enhance groundwater recharge, reduce runoff losses, and improve water resilience. Techniques such as check dams, retention basins, and infiltration trenches have proven effective in capturing surface runoff, directing it into aquifers or recharge zones, mitigating environmental damage, and strengthening local water security **(Negm, 2020)**.

Recent remote sensing studies in the Wadi El-Assiuti Basin further highlight the potential for groundwater recharge in this region. These studies identify specific sub-basins as optimal sites for constructing artificial recharge structures that could substantially improve water availability and security **(Kamel & El Ella, 2024)**.

The most common floodwater harvesting approaches include the construction of low-cost gabion dams and masonry check dams, along with surface groundwater recharge techniques. At present, the majority of floodwater harvesting installations are concentrated in Sinai **(Omran, 2020)**. Numerous studies have identified additional prospective sites for check dam construction (Fig. 5), and there are plans to raise the height of the Rawafaa Dam to increase storage capacity **(Omran, 2020)**. Moreover, diversion dams and water-spreading dykes are expected to be constructed alongside check dams in central and northern Sinai to further maximize floodwater utilization.

a **b**

Fig. 4. a. El-Alamein, and **b.** El-Galalah Water desalination plant (**https://www.entropie.com/newsroom/press/contract-award-sea-water-desalination-plant**)

4. Risks and challenges

. The sustainability of Egypt's water supply is increasingly threatened by climate change, the construction of the Grand Ethiopian Renaissance Dam (GERD), a rapidly growing population that now exceeds 100 million, and long-standing issues of inefficient water management. While Egypt's demand for water continues to rise, its renewable water resources remain relatively constant **(Abdelhafez *et al.*, 2020)**.

According to the Egyptian Ministry of Water Resources and Irrigation, the country currently faces an annual water deficit of ~20 billion cubic meters. National water needs are estimated at ~80 billion cubic meters per year, whereas the available freshwater supply within Egypt's borders amounts to only ~60 billion cubic meters **(Hamada, 2017)**. This growing imbalance, compounded by climate change, inefficient irrigation practices, and pollution, poses serious risks to Egypt's food security and long-term sustainable development.

Egypt's water resources are exposed to three major risk factors, the first of which is the construction of the Grand Ethiopian Renaissance Dam (GERD). Located on the Blue Nile about 15 km from the Sudan–Ethiopia border (Fig. 6), the GERD was launched in April 2011. With a reservoir capacity of 63 BCM and a hydropower capacity of 6,000 MW, it is the largest hydroelectric power plant in Africa and one of the largest water reservoirs worldwide **(Gebreluel, 2014)**. For Ethiopia, the dam is expected to generate substantial economic benefits, including job creation, improved living standards, and enhanced energy security.

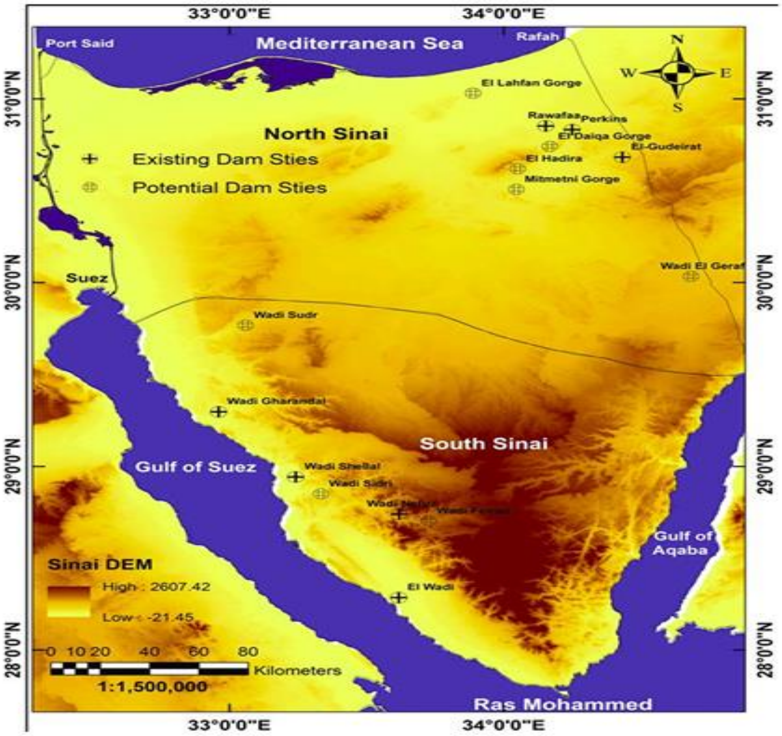

Fig. 5. Existing dams and potential sites for dams in Sinai **(Omran, 2020)**

Egypt is particularly concerned that the GERD could significantly reduce the Nile water flows, threatening critical sectors such as irrigation, drinking water supply, and hydroelectric power generation **(Ahmed *et al.*, 2024)**. The uncertainty surrounding the dam's long-term impacts has intensified Egypt's efforts to secure alternative and reliable water sources.

According to **Heggy *et al.* (2021)**, Egyptian experts reported that a ~20–34% reduction in Nile water levels could occur if the reservoir filling coincided with a drought peak. During the initial filling of the GERD in July 2017, Egypt's annual water share was reduced to ~18 billion m^3. This reduction threatens approximately 5 million feddans of agricultural land, along with a decrease in electricity generation from the High Aswan Dam (HAD) by 4,500 gigawatt-hours—equivalent to ~37%—potentially leading to a cumulative deficit in power supply over the next four decades.

The agricultural sector is expected to face multiple impacts. Insufficient water supply may fail to meet crop requirements, while deterioration in water quality, increasing salinity levels, and higher water circulation rates may further reduce productivity **(Abotalib *et al.*, 2019)**.

Previous investigations into the GERD have focused on three main areas:

1. Monitoring water level, surface area, and volume of the GERD reservoir,
2. Assessing land deformation associated with dam construction, and
3. Examining the implications of reservoir-filling scenarios on the Nile water allocations for Egypt and Sudan.

Elsayed *et al.* (2020) predicted that Egypt's energy sector would be substantially affected if reservoir filling occurred during drought conditions. Similarly, **Abdelhaleem and Helal (2015)** suggested that Egypt's water share reduction should not exceed 5–15% in order to mitigate adverse effects on the HAD reservoir.

More recently, **Ahmed *et al.* (2023)** assessed spatiotemporal variations in surface area, volume, water storage, and precipitation for the GERD and four other reservoirs in Sudan and Egypt. Their findings indicated no statistically significant changes in reservoir characteristics during phases I and II of GERD filling, largely because of the substantial floods that occurred in the sub-basins feeding these systems. However, the study warned that if future filling occurs during drought years, both Egypt and Sudan will face severe consequences.

Fig. 6. The Grand Ethiopian Renaissance Dam (GERD)

i. High pollution rates

Water pollution constitutes one of the most pressing threats to Egypt, particularly within the Nile River System, which includes the main Nile, canals, and drains. In recent decades, population growth, expanded irrigated agriculture, industrial development, and increasing human activities along the Nile have escalated pollution pressures. Industrial effluents, untreated sewage, and agricultural runoff degrade water quality, directly affecting millions of Egyptians who rely on the river for daily needs.

The Nile bifurcates into the Damietta and Rosetta branches at the Delta Barrage, north of Cairo **(Abdo, 2010)**. Studies have identified several threats:

- The Rosetta branch faces long-term degradation from growing human activity **(Elewa *et al.*, 2009)**.
- The Damietta branch is affected by meteorological conditions, water releases, emissions from Talkha Power Station, municipal waste at El-Serw, agricultural residues behind Faraskour Dam, and saline intrusion from the Mediterranean Sea **(Abdo, 2010)**.

Egypt maintains ~30,300 km of major and minor canals **(El Gamal, 2000)**. Assessments of canal and river water quality indicate concerning trends:

- The **Ismailia Canal** ranged from good to poor for drinking and aquatic life but remained excellent for irrigation **(Goher *et al.*, 2014)**.
- **Trace metals** (Cd, Cu, Pb, Ni, Cr) were within WHO (2008) and EPA (2009) permissible levels, except Fe and Al, which exceeded limits due to steel and iron industry effluents **(Hassouna *et al.*, 2014)**.
- **Satellite data** have been shown to support water quality monitoring and parameter estimation **(El-Saadi *et al.*, 2014)**.
- A comprehensive study at 24 sites between Aswan and Cairo revealed declining water quality indices, from marginal to bad for general use, though drinking-water indices varied from marginal to good **(Abdel-Satar *et al.*, 2017)**. Reduced Nile water inflows due to GERD may further diminish dilution capacity.

The Rosetta branch suffers particularly from municipal, agricultural, and industrial effluents, including discharges from El-Rahawy sewer, Soble runoff, and Kafr El Zayat industrial drains. WQI assessments classified water as poor to very poor for irrigation and aquatic life **(Abdo *et al.*, 2022)**.

Heavy metal studies have also raised health concerns:

- **GIS modeling** of the Nile Delta soils mapped Cd, Co, Cu, Pb, Ni, and Zn concentrations **(Abuzaid *et al.*, 2023)**.
- **River water monitoring** between Aswan and Cairo indicated improvement in water quality due to higher water levels, though northern areas (e.g., Greater Cairo) remain highly polluted **(Hegab *et al.*, 2025)**.
- **Toxicological assessments** showed excessive cadmium, copper, lead, manganese, and zinc levels in water and fish tissues (O. niloticus and C. gariepinus). Hazard indices indicated moderate health risks, necessitating stronger regulatory oversight **(Khedr & Ghannam, 2025)**.

ii. Desalination energy and cost

Although desalination offers a strategic option to mitigate freshwater shortages, it faces several challenges: high energy consumption, dependence on fossil fuels, elevated costs, and environmental impacts, including greenhouse gas emissions and brine discharge **(Zolghadr-Asli *et al.*, 2023)**.

Egypt currently produces ~475 million m³ annually from desalination. For decades, the technology was not considered viable due to cost barriers relative to the Nile-supplied water. Costs per m³ depend on plant capacity, making agricultural use commercially unfeasible **(Fath, 2018)**. More recent investigations have focused on **brackish aquifers** along the northern Mediterranean and North Sinai, which have lower salinity than seawater and thus lower desalination costs **(Asif *et al.*, 2024)**. Aquifers with ~10,000 ppm salinity are economically feasible for irrigation purposes.

With global energy demand rising and climate concerns intensifying, reliance on fossil fuels for desalination is unsustainable **(Zapata-Sierra *et al.*, 2021)**. The integration of renewable energy—solar, wind, and nuclear—into desalination processes is increasingly attractive **(Hassan *et al.*, 2024)**. Solar-assisted desalination, in particular, offers high potential, especially in arid regions with abundant sunlight and low operating costs **(El Tawail *et al.*, 2009; Zapata-Sierra *et al.*, 2021)**.

In line with Egypt's Vision 2030, new desalination strategies emphasize renewable integration. Solar thermal desalination systems are generally classified as:

- **Direct systems**: where evaporation and condensation occur in one unit.
- **Indirect systems**: comprising separate solar collectors and desalination units.

iii. Effects of desalination brine on marine ecosystems

Desalination plants produce concentrated brine, typically discharged into the sea. This effluent is denser and hypersaline, forming plumes that settle along the seabed and negatively affect benthic ecosystems **(Pramanik *et al.*, 2017)**.

Brine impacts depend on marine hydrodynamics and effluent composition. Alongside elevated salinity, residuals often include chlorine, heavy metals, and biocides:

- Chlorine, used in RO systems to prevent fouling, is typically dosed at ~2mg/ L. EPA guidelines specify chronic and acute limits of 7.5µg/ L and 13µg/ L, respectively, for seawater **(Ciocanea *et al.*, 2013)**.
- EPA thresholds for salmonids are even stricter (2– 10µg/ L).
- Trace metals (nickel, iron, chromium) have been detected in RO brines but usually below critical thresholds **(Ladewig & Asquith, 2012; Panagopoulos & Haralambous, 2020)**.

In Egypt, the Nuweiba desalination plant discharged ~623kg free chlorine, 469kg combined chlorine, 207kg chloroform, and 76kg bromoform annually into the Gulf of Aqaba **(Hamed *et al.*, 2017)**. By-products such as chloroform (CF), dichlorobromomethane (DCBM), dibromochloromethane (DBCM), and bromoform (BF) were also detected, with BF and CF accounting for ~98% of total trihalomethanes. Additionally, oxygen scavengers used to reduce chlorine emissions decreased dissolved oxygen, further stressing ecosystems **(Khedr, 2016; Hamed *et al.*, 2017)**.

To safeguard ecosystems, the Egyptian Environmental Affairs Agency requires discharged brine to stay within ±5% of natural salinity levels, necessitating advanced hydrodynamic modeling to validate discharge practices.

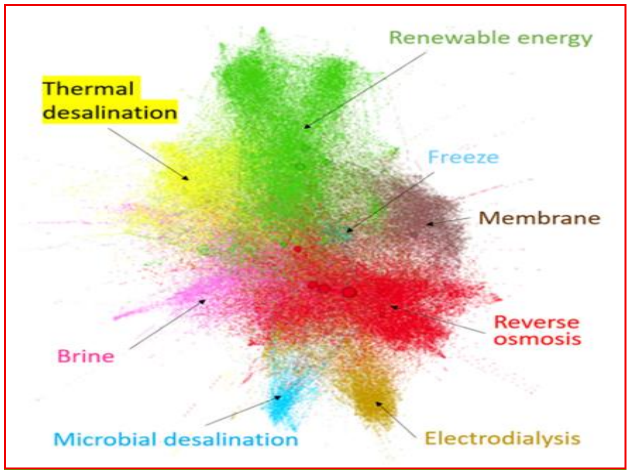

Fig. 7. Relationship between desalination publications **(Zapata-Sierra *et al*., 2022)**

5. Future solutions for water scarcity

Several strategies have been proposed to address future water scarcity challenges:

a. Water conservation

Efficient water utilization is essential for reducing wastage. Methods such as drip irrigation, rainwater harvesting, and the reuse of greywater for irrigation can substantially conserve water resources. Public awareness campaigns and educational programs also play a critical role in encouraging responsible water use at the household and community levels.

b. Technological advances

Innovations in desalination technology hold promise for converting seawater into potable water, particularly for arid regions. Continued improvements in cost efficiency and energy integration will enhance the feasibility of large-scale deployment.

c. Biological treatment and recycling

The application of biological treatment methods, such as aerobic fermentation, facilitates the reuse and recycling of water. This reduces reliance on freshwater sources and eases stress on existing supplies.

d. Policy and management

Effective water governance requires the integration of policies that promote sustainable water use while leveraging new technologies. Integrated Water Resource Management (IWRM) provides a holistic framework, addressing social, economic, and environmental needs. Success depends on the cooperation of governments, the private sector, civil society, and academia to ensure equitable access to water.

e. Community involvement

Engaging local communities in water management ensures that solutions are tailored to the unique needs and conditions of each area. Community-driven initiatives empower individuals, foster accountability, and help establish long-term sustainable practices.

f. Adaptation and resilience to climate change

Climate change exacerbates water scarcity through altered precipitation patterns, droughts, and extreme weather events. Adaptation strategies should include climate risk assessments, mapping vulnerable populations, and developing appropriate policy responses. Investments in climate-resilient green and blue infrastructure, as well as innovative technologies, are vital for enhancing resilience. The Footprint Standard system provides one such framework for promoting adaptation and resilience.

CONCLUSION

Water Scarcity is one of the most pressing global issues of our time, affecting people from one end of the world to the other, threatening ecosystems, food security, human and animal health, culture and the economic prosperity. With climate change and populations increasing, the scramble for clean, accessible water is outstripping supply. We must work on a variety of fronts to solve this crisis—in sustainable water management, in infrastructure development, in conservation, in international collaboration. In this review, various solutions have been suggested to work on, e.g, artificial groundwater, water harvesting, wastewater reuse in addition to desalination technology in Egypt and around the world.

RECOMMENDATIONS

The objective of Egypt s National Water Resources Plan for 2037, established by the Ministry of Water Resources and Irrigation, is to safeguard the available water resources, which include their allocation of the Nile water, nonconventional resources, agricultural water, and groundwater. The plant has a goal to decrease water usage for agriculture, industrial, and domestic use to 80 % of current levels. The plan relies on formulating scientific solutions to address the parent circumstances and future challenges via various programs, which encompass the implementation of water desalination technology in coastal regions, water reuse, advanced irrigation techniques, and water harvesting in areas beyond the Nile Valley. Addressing these issues could have various benefits, including:

- Enhanced water quality to ensure safety for humans, livestock, crops and aquatic organisms.

- Continually monitoring a waterway's chemical characteristics is crucial to identifying pollution sources and safeguarding ecosystems, thereby securing water safety for both people and the environment. Regulating these factors is essential for preserving the ecological equilibrium of river systems.
- Early prevention and mitigation of rivers pollution will enhance the population’s health and productivity, safeguard biodiversity of numerous species, and can save economic losses in sectors dependent on clean water.
- Application of artificial groundwater recharge techniques in the eastern desert, where evaporation losses are substantial.
- Implementation of renewable energy sources, including solar power for recharge activities and replenishing non-renewable deep aquifers such as the Nubian Sandstone Aquifer.
- Evaluating the extensive environmental Effects of artificial recharge on the worldwide hydrological cycle.
- Analyzing the interplay of various forms of aquifer obstruction and formulating a propriate management measures
- Examining the feasibility of reintroducing floodwater accumulated in depressions, such as Toshka, into deep aquifers to mitigate evaporation losses.
- The construction of several artificial groundwater recharge dams and water-spreading dykes are anticipated in central and northern Sinai.
- Enhancing the efficiency of seawater desalination via integrating green-synthesized nano-composites and nanofluids for solar cells technology, resulting in an optimized thermal performance and a higher evaporation-condensation cycles, maximizing freshwater output as a more efficient, cost-effective and sustainable renewable desalination process.

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