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Water desalination in Egypt; literature review and assessment

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A B S T R A C T

The increasing demand for water in urban and industrial areas in arid and semiarid coastal zones has led to the search for alternative nonconventional water resources.. Desalination plants are the most feasible solution to the huge water demand in arid regions, especially in Egypt, with its limited water resources of the Nile River and expected drought due to climate change and upstream dam construction. Many desalination technologies, such as thermal and membrane technologies, are used. Thermal desalination includes multistage flash desalination, multi-effect desalination, and desalination by vapor compression. Membrane desalination involves RO, forward osmosis, and electro dialysis. (RO) desalination plants are the most significant technique for desalinated water in Egypt. However, the treatment of brine wastewater is still a challenging problem. Hypersaline water effluent, as a byproduct of seawater desalination, has a negative impact on the marine ecosystem if it is discharged inadequately. In the past decade, Egypt has launched many large-scale projects along Red Sea and Mediterranean coasts to cope the recent economic growth.

In this research a review of taxonomy of many related publications, and comparison has been made between the different seawater desalination techniques to determine the advantages and disadvantages of each of them, as well as to know the best technology that can be used in Egypt. The Egyptian state's plan to address the excessive demand for water resources as a result of the continuous population growth was reviewed by making a strategic plan for 30 years. It was divided into five-year plans, some parts of which have been completed, and the rest of the plan is being completed to present significant comparisons and enable the derivation of informative conclusions.

1. Introduction

However, water covers approximately three-quarters of the surface of the earth but over 97.2 % of the total water resources are saline or brackish water bodies. More than 2.1 % of the remaining 2.8 % of the available freshwater is tied in ice caps, glaciers, atmosphere and soil moisture. Therefore, livelihood of humans and various agricultural technologies and activities depend upon the remaining 0.7 %, of the freshwater supply of lakes, rivers, and groundwater, which is estimated to 8.5×10^9 m^3 [1].

Water scarcity caused by non-integrated water resources management, pollution, climate change and population growth, is the most urgent problem. This has severely affected biological diversity by threatening more than two-thirds of the natural habitat [2]. The supply of freshwater has become a worldwide interest, as it is the core of human and varied biological lives on the earth. Egypt's per capita annual water supply will drop from 550 m^3 today to 500 m^3 by 2025, attaining the UN threshold for absolute water scarcity. Since Egypt has approximately 3000 km of coastlines on both the Red Sea and the Mediterranean, so desalination is the most feasible and promising solution to provide fresh water [3].

Around the world, many countries rely on desalinated water for more than 50 % of their domestic water use to avoid real threats to

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resource sustainability and to meet the urgent need of industrial water increase and supply of drinking water [4,5]. In 2015, approximately 18,426 desalination plants were installed and operated in 150 countries, providing approximately 86.8 $\times$ $10^6 m^3$ of fresh water to more than 300 million people every day [6]. In general, the Middle East ranks as the largest consumer of desalinated water. Drought and desertification conditions strongly promote the treatment of unconventional water resources to solve the scarcity on water demand [7].

Mazen Abualtayef et al. used CORMIX v 9.0 to make a Numerical simulation of liquid brine discharge in Deir al-Balah desalination plant in order to study the dilution and dispersal behavior of brine through eight disposal systems, including single port, multiport diffuser, unidirectional multiport diffuser, and multiport diffuser. After this process, the simulation results for different downstream configurations show that the unidirectional multi-port downstream is the optimum configuration for the design process, which can meet the criterion of disposal in the most difficult ambient conditions at the edge of the mixing zone to less than about 1.25 % that is higher than the salinity of brine [8].

Katteb et al. conducted a numerical study for the dilution and dispersion of fouka desalination plant brine effluent marine outfall using CORMIX for near-field areas. Delft-3D was used for the far-field mixing area, and the results showed that if input data are of high quality to the CORMIX model, it becomes a powerful and reliable management tool for brine effluent environmental impact assessment [9].

The Kingdom of Saudi Arabia produces the largest desalinated water in the world, about one-tenth of the desalinated water produced every day [10]. The United Arab Emirates has become the world's second-highest seawater desalination country, with a desalination capacity of $8.4{\times}10^6$ m^3/day, and more than 85 % of desalinated water comes from desalination plants [7]. In Egypt a plan to expand the desalination plan to produce 1,307,690 m^3 / day by 2025, with emphasizing on the coastal and remote areas [11].

However, seawater desalination technology is negatively characterized by its expensive cost, high energy consumption, and hyper saline water effluent which still exert adverse impacts on the environment. Therefore, to ensure the sustainable use of seawater desalination technology, appropriate methods should be developed within the framework of environmental impact assessment (EIA) to investigate and reduce costs and negative impacts of the desalination process, especially brine effluent waste, as much as possible [12–13].

Currently, 90 seawater desalination plants are running in Egypt, with a total capacity of 1.3 $\times$ 10^9 m^3, at a cost of 12 $\times$ 10^9 Egyptian pounds, 76 plants have been completed and fully operated, with a daily capacity of 850 $\times$ 10^3 m^3. The remaining 14 plants with a daily capacity of 450 $\times$ $10^3 m^3$ will be working by 2050. The new plan aims to reach 6.4 $\times 10^6$ m^3/day of fresh water, at a cost of 134 $\times$ 10^9 Egyptian pounds [11].

This study presents a taxonomy of the different desalination technologies in Egypt as a strategic option to support the Egyptian water sector, for plants located along the Red Sea and the Mediterranean coasts.

2. Water sector in Egypt

Currently, the total annual rainfall in Egypt is nearly about 18 mm, and approximately mainly on the north coast, with an annual average rainfall of about 150 mm. Most of rainfall occurs at Sinai Peninsula, and along the Mediterranean and Red Sea coast, that represents $1.3{\times}10^9$ m^3/year of renewable water resources recharging shallow aquifers [14].

The Nile River provides 97 % ($55.5{\times}10^9$ m^3/year) of Egypt's annual renewable water resources as shown in Fig. 1, this amount is threatened due to climate changes and new dam construction in the upstream. This represents decrease of annual capita share from 800 to 550 m^3/cap/yr from year 2004, to year 2022 respectively. Nonconventional water resources include wastewater reuse, seawater desalination, rainwater harvesting, and brackish groundwater desalination. The groundwater extracted from western desert provides $1.65{\times}10^9$ m^3/year, while municipal wastewater reuse is about 2.9 $\times 10^9$ m^3/year, while the reuse of agricultural wastewater capacity in the Nile Valley and Delta is expected to be $9.7{\times}10^9$ m^3/ year [15].

In the last 20 years, the use of groundwater in Egypt has largely increased. The Egyptian Ministry of Water Resources has established a groundwater management department to coordinate the use of groundwater. All major aquifer systems in Egypt contain vast quantities of brackish nonrenewable groundwater aquifers: the Nubian sandstone aquifer, the Moghra aquifer, the tertiary aquifer, carbonate rock complex aquifers, and fissured basement complex aquifers. The Nile and delta aquifers are renewable aquifers. As the current price of brackish water desalination is still low, incremental interest has increased towards its exploitation. Brackish water desalination plants in Egypt confirm the potential of this water resource. The coastal aquifers are located near the northwest coast with limited fresh water extraction due to the presence of salt water underneath this aquifer, although it is considered partially renewable due to rainfall recharge [17].

3. Water sector governance in Egypt

The Ministry of Water Resources and Irrigation (MWRI), Ministry of Agriculture and Land Reclamation, Ministry of Housing, Utilities and Urban Communities (MOHUUC) are the three governmental entities responsible for the management of water resources in Egypt. The mandate of the MWRI Its role is to formulate and implement the general policy for the development and management of surface/groundwater and related water resources (e.g., flash floods, rainwater harvesting and desalinated water) at the national, regional and sub-regional levels.

The Ministry of Agriculture and Land Reclamation is responsible for achieving food security by renovating the agricultural sector to improve the efficiency of resource use and investing in each of the elements of geographical distinction between the different agricultural regions and available water resources. The MOHUUC mainly

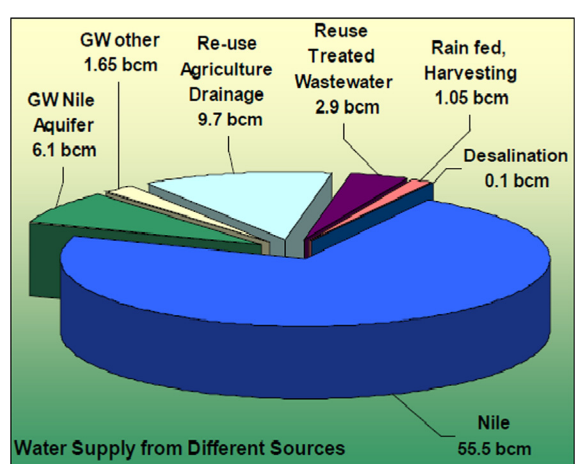

Fig. 1. Sources for Water Supply in Egypt [14].

constructs and operates all drinking, wastewater, and desalination plants for the municipal and industrial sectors. The Ministry of Irrigation launched many programs to support the improvement of environmental and water resource management, focusing on the integration of water resource management [17].

4. Desalination goal

Desalination in Egypt started has started for more than 100 years ago with a main purpose of drinking water supply to coastal and remote areas for petroleum and electricity company staff. Most desalination plants are based on thermal technologies. In recent years, many membrane-based plants have been constructed in different economic sectors. In the last decade, the number and capacities of desalination units have increased 45 % Multi-Stage Flash (MSF) and 42 % (RO) of world capacity, especially in the Gulf countries. It is indispensable to explore new water resource management techniques to improve efficiency and prevent pollution and add nonconventional water resources to narrow the gap between water supply and demand. Egypt's comprehensive water resources policy was clearly stipulated in the 2020–2050 National Water Resources Plan. The increase in desalinated water production from 850×10^3 m^3/day in 2020 reached 1.3 $\times10^6$ m^3/day and even reached 6.4 $\times10^6$ m^3/day in 2050. Not only is the public sector encouraged to invest in water desalination plants, but the private sector is also supported in applying modern technology for desalination. The great achievements of seawater desalination technology have changed the cost of seawater desalination in many applications from expensive to competitive. Current technology is viable for tourist villages on the north coast and the Red Sea because it is far from conventional water sources, making transport very expensive and vulnerable to pollution problems. Despite research and development, energy requirements and membrane technologies are still limiting factors. Therefore, Egypt's future vision is not theoretical in the field of desalination. It is based on a real move towards the use of renewable energy, so solar energy will be used to operate the high compression pumps required for the modular RO system. The reasons are obvious, since Egypt has great potential for brackish water wells, immense amounts of solar radiation in remote areas and future integrated development projects are located far from the Nile River water.

Desalinated water as a nonconventional water resource should be considered a necessary measure for water security in Egypt, and the government should make more efforts to improve the technologies used for desalination and to investigate power source alternatives.

5. Desalination in Egypt

Desalination is considered a renewable water resource in many parts of Egypt, owning approximately 2,400 km of coastline on the Red Sea and Mediterranean, as well as large brackish water aquifers. Seawater desalination is currently being carried out in the coastal areas of the Red Sea to provide sufficient domestic water for villages and touristic resorts because the economic value of unit water in these areas is sufficient to cover the cost of desalination [18].

More than 100 years ago, Egypt began desalination, which appeared in the form of a large distillation tank in the Helwan area to produce fresh water for domestic use in remote areas of public water supply networks. However, due to increasing population growth and urban sprawl in coastal and remote areas, Egypt began applying advanced desalination technologies in the mid-1970 s. Between 1975 and 1982, Egypt installed three different types of electro dialysis (ED) equipment with capacities ranging from 50 to 1000 m^3/day, and the salinity of the influent water was between 2000 and 10,000 ppm.

At present, Egypt encourages both the public and private sectors to expand in desalination plant construction and uses of different technologies. Historically, the application of desalination technology in Egypt began with distillation, then (ED), and finally (RO). The tremendous achievements of global seawater desalination technology have changed the cost of seawater desalination in many applications from "expensive" to "competitive". Therefore, the currently available technology is feasible for tourist villages on both the northern coast and the Red Sea because they are remotely located from conventional water resources, so the water supply from public networks will have high transportation costs and higher opportunities for water pollution.

Desalination is mainly used to provide additional drinking water to coastal cities and for oil/energy sector power plants located in remote areas and deserts. Some public institutions, such as the South Sinai Rehabilitation Bureau, also operate small desalination plants for the remote villages in South Sinai.

For a long time, desalination in Egypt was not considered among the alternative choices for stakeholders due to its high cost relative to other conventional resources. Currently, the average cost of desalination for one cubic meter of seawater ranges from 0.7 to 0.9 USD [19]. In addition, desalination provides domestic water with feasible fees, especially in remote areas where the cost of constructing pipelines to transport water from the Nile is relatively high. Desalination can be used as sustainable domestic water in many places. Desalination uses may expand the future to cover other purposes, such as agriculture and industry, depending on the rate of improvement in the technology and the cost of energy required. If renewable sources of energy can be used, desalination will be economical for other uses. However, brackish groundwater with a salinity of approximately 10,000 ppm can be desalinated at a reasonable cost, offering potential for desalinated water in agriculture. The volume of desalinated water in Egypt is now approximately 475×10^6 m^3/year [11].

Now at Ministry of Military Production, some belonging factories are producing treatment and desalination devices. The Military Production in Egypt and International Desalination and Water Treatment group (IDWT) signed a contract in 2019 to establish a company specializing in the manufacture of desalination and water treatment plants, including a large-capacity device such as that in Hurgada. However, the private sector has introduced RO and RO equipment in many resorts to meet the real needs and growing needs of households. This has opened the market for the public sector and some private companies to start assembling/producing a wide range of (RO) devices [18].

6. Effect of brine on the marine ecosystem

The brine produced from RO seawater desalination plants is classified under the category of negatively buoyant effluents. Commonly, brine is discharged directly into the sea, forming a hypersaline and high-density plume of water that diffuses along the benthos and harms the benthic ecosystems [20,21]. Brine effluents have negative impacts on marine environments that vary based on the hydrodynamic ability of marine ecosystems to dilute these discharges and on the physical and chemical properties of these discharges, in addition to heavy metals, biocides, and other chemical pollutants that may be harmful to marine habitats [4]. Salinity controls the distribution of marine habitats; most of these habitats adapt salinity deviations up to 45 psu, but continuous exposure to high salinity could reduce the diversity of marine habitats [22]. Continuous disposal to brine prevents the arrival of solar radiation to benthic plankton species, which leads to a reduction in photosynthesis process continuity, in addition to other pollutants that may be included. Chlorine is mainly used in the RO desalination process to avoid fouling. A dosage of 2 mg/l chlorine is injected through the desalination cycle. Traces of nickel, iron, and chromium could be detected in the RO brines but with noncritical concentrations [23]. The U.S. EPA defines the water quality criteria by of chronic Criterion Continuous Concentration (CCC) and acute Criterion Maximum Concentration (CMC), for chlorine in saltwater concentrations are 7.5 and 13 μg/l, respectively [24]. The U.S. EPA recommends 2 μg/l for salmonid fish and 10 μg/l for other marine organisms to protect sensitive aquatic life from chlorine chronic effects. In Egypt, the EEAA (Egyptian Environmental Affairs Agency) stated that the primary needed dissipation of pollutants should not exceed +/-5% to provide good dilution characteristics for the saline concentration and be safe for marine life in its vicinity, which also implies a hydrodynamic modeling study to ensure this regulation.

7. Environmental regulations and requirements

The main environmental challenge facing the seawater (RO) desalination process as a potential approach to meet the water needs shortage is its brine disposal effluents and its negative impacts. As a sub product of the RO process, large amounts of brine are produced with a concentration of salinity more than twice that of the feed water, which is usually recharged to seawater [13]. Environmental management and monitoring tools are essential for controlling the integrity of the environment and collecting accurate knowledge for the behavior of environmental phenomena to be controlled. The environmental standards that regulate the activities of effluent disposal into marine systems are not unified universally. Hence, each country tends to formulate its own water regulations that are most suitable for practice [4]. At present, the regulations of effluent disposal are mainly for MED based on the concept of mixing zones at the point of discharge. The dimensions and the standard of water quality at the border of these zones are defined according to the capacity of the receiving water body to dilute the effluent and to ameliorate both the spatial and temporal deterioration of aquatic systems [26]. Physical and numerical models are effective as prediction tools to control and minimize the negative environmental impacts through the hydrodynamic simulation of brine disposal into marine environments under different ambient conditions [27]. According to the environmental impact assessment, the mixing efficiency of the brine disposal systems should be studied carefully. In Egypt, with its unique coral reefs and marine ecosystem, the EEAA implies standards, directives, and conditions to control coastal activities to protect the marine environment from pollution. The EEAA prevents any action that may affect the marine ecosystem. Recently, different alternatives to hypersaline water dispersion standards were set. Egypt has recommended best practice regulations for liquid waste effluents based on sea water desalination hydrodynamic pollutant dissipation and environmental standards in the UNEP Mediterranean Assessment and Guidelines (2003). UNEP standards are considered adequate for modeling saltwater diffusion and determining possible permissible levels. The characteristics of UNEP regulations of the discharge of liquid wastes to the marine environment should not exceed the surrounding salinity at the edge of the 100-meter diameter Regulated Mixed Zone (RMZ) centered on the provision point by more than 10 %.

8. Water desalination technologies

The most popular seawater desalination technologies are currently revolving around two pillars:

8.1. Thermal desalination technology

The distillation process is the earliest desalination technology and is commonly used for seawater. A solar energy source is frequently used in this method. Thermal desalination can be classified into three main groups as follows.

8.1.1. Multi-stage flash (MSF)

A desalination process that distills seawater by pumping water to steam in multiple stages of heat exchangers. The boiling point of liquids is directly proportional to the applied pressure. This method is used in desalination plants with large production capacity and a market share reach of 20 % from the total world production capacity. Within this process, evaporation and condensation occur through boiling seawater and condensing the vapor to produce distilled water [29]. In addition, the energy supplied during evaporation may be recovered by condensation. This process can produce freshwater with a high quality of less than 30 ppm total dissolved solids (TDS), as shown in Fig. 2. (MSF) units can produce large quantities of fresh water up to 75000 m^3/d for each unit that can be used in many human purposes. In Sinai, "Ayoun Mosa" (MSF) plant has a capacity of 2×5000 m^3/day, with a feed seawater salinity of 48000 ppm, a feed seawater temperature of 27 °C, and a brine blowdown temperature of 29 °C [30].

8.1.2. Multieffect distillation (MED)

Multieffect distillation (MED) desalination is one of the most successful desalination technologies. MED desalination plants usually have a series of evaporators to produce distilled water, with heat supplied from external steam sources, such as power plants, sugar, paper and pulp, and dairy factories. At present, using MED for seawater desalination presents a good market share in the Middle East. The energy required for (MED) desalination is 6.5–11 kwh/m^3 less than that required in (MSF). Many desalination plants in Egypt are using (MED) desalination processes, such as Abu Qir (MED), which produces 10000 m^3/day, and El Sokhna (MED), which produces 8000 m^3/day using two distillation units, as shown in Fig. 3 [32].

8.1.3. Pressurized vapor desalination (VC)

In this distillation process, seawater is evaporated by applying heat delivered by pressurized vapor. As the vapor compression process increases the pressure and temperature, it is possible to use latent heat during condensation to generate additional steam. The required energy for (VC) desalination is 7–12 kwh/m^3.

8.2. Membrane desalination

As shown in Fig. 4, seawater was desalinated using membranes to remove salts and undesired minerals from water solution when passing through it. Membrane desalination is classified into the following three main groups.

8.2.1. Reverse osmosis (RO)

The opposite is true for the osmosis phenomenon, where water moves from a higher to a lower concentration solution through a semipermeable membrane using high pressure. Water can be passing by several stages, where salts and minerals are separated. For seawater desalination, a pressure of 50 to 70 bar is applied, depending on the type of membrane and the design of the plant. The (RO) desalination plants consist of the primary treatment to remove suspended particles, sand, and silt and then an anti-scale injection system to remove calcium and sulfate salts that deteriorate the membrane performance. High-pressure pumps are used within this process, presenting approximately 45 % of the plant cost, and are needed to increase the water pressure up to 70 bar.

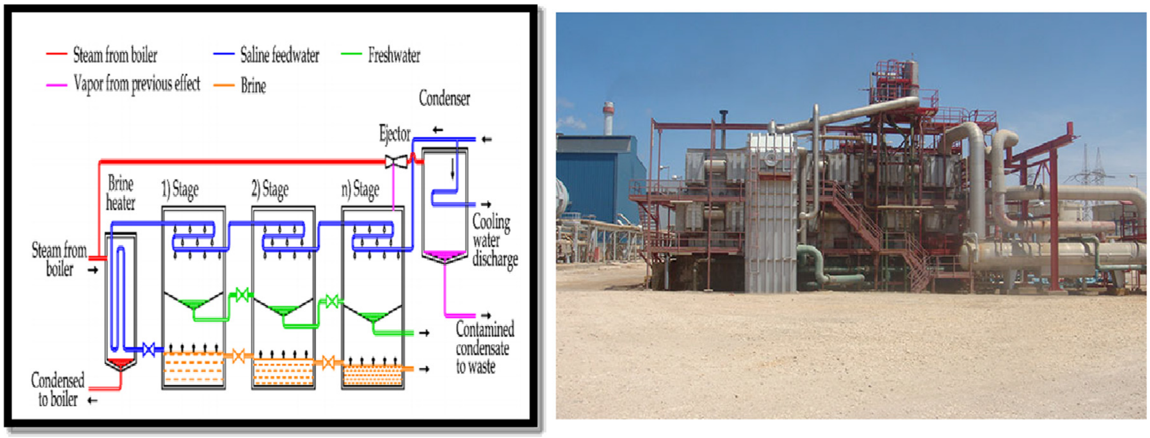

Fig. 2. Multistage flash desalination plant at Ayoun Mosa, Egypt [29].

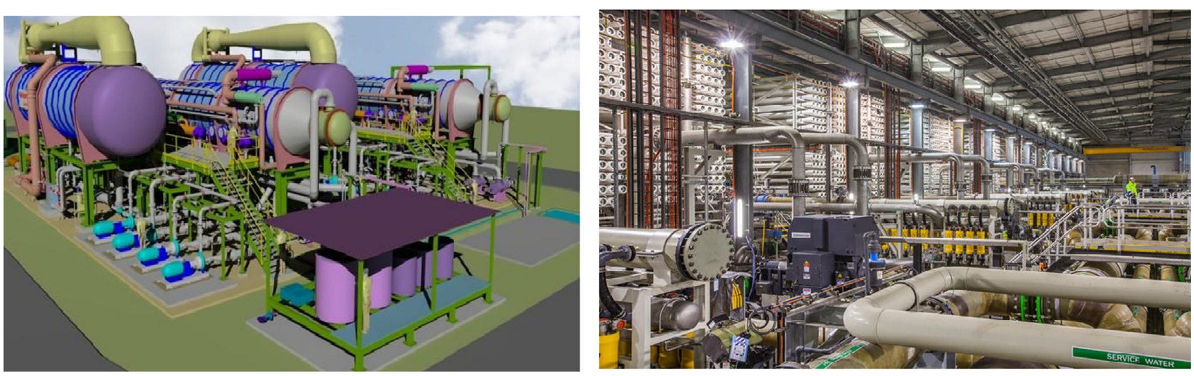

Fig. 3. Multi-effect desalination plant at 4000 m^3/day in each Suez, Egypt [33].

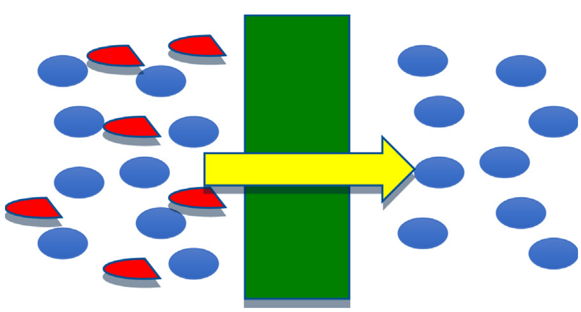

Fig. 4. Membrane Desalination process [32].

Membranes have a 3- to 5-year lifespan and should be replaced when their cost reaches 35 % of the total cost [11]. The Egyptian government is expanding the construction of RO desalination plants with a capacity of 150,000 m^3/day in new cities; for example, at El-Galalah, El-Alameen, and East Port Said, Fig. 5 shows the El-Galalah desalination plant.

8.2.2. Forward osmosis (FO)

This process follows the natural osmotic process, in which the water moves from low to high concentration areas, consuming less energy than that used in the RO process, leading to a reduction of half of the cost [11].

8.2.3. Electro dialysis (ED)

This process transferred salt ions from a solution through ion exchange membranes under the influence of electric potential differences. This process is used for desalinating brackish and saline water on a small scale. It is also used in treating rejected brine from the RO process [11]. Fig. 6 shows the distribution percentage of desalination techniques used all over the world.

9. Energy consumption for different desalination techniques

The desalination process techniques consume electrical energy, which RO techniques can consider the lowest electricity consumer, but the multistage flash technique requires the highest intensive energy, as shown in Table 1.

All of these techniques have advantages and disadvantages; these parameters represent the construction and operation cost, water treatment required before desalination, energy required, quality of produced water, recovery ratio, design capacity for each technique, and the needed experience for the operational staff. All of these parameters are briefly explained for each technique in Table 2.

10. Percentage of (RO) plant components

Table 3 shows the RO desalination plant components and the percentage of each. High-pressure pumps and membranes represent the main components of the plant, accounting for up to 35 % of the plant, buildings and civil constructions and 30 % of the other components, as shown in the table below.

11. Construction and operational cost for RO plants

The cost of construction and operation for desalination plants that work by the RO technique is shown in Table 4, which includes

Fig. 5. El-Galalah (RO) Water desalination plant [33].

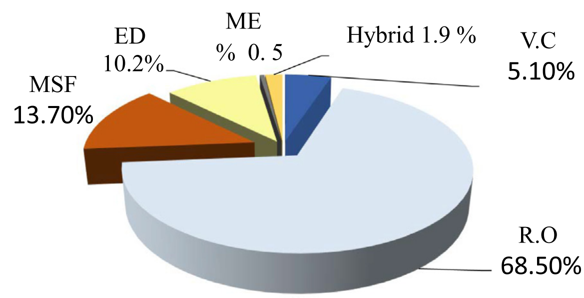

Fig. 6. Percentage of desalination techniques distributed all over the world [32].

Table 1
Energy consumption for each technique.

Desalination Techniques	Total Equivalent Electrical Energy (kwh/m^3)
Multi-Stage Flash ((MSF))	13.5–25.5
Multi-Effect Distillation ((MED))	6.5–11
Mechanical vapor pressure (MCV)	7–12
(RO) (RO)	3–5.5

investment cost, operational cost as membranes and chemicals, and the cost of maintenance.

12. Types of RO plants using membrane desalination

Brackish water desalination plants are desalination plants that operate at salinities of less than 10,000 ppm. Saline water desalination plants are desalination plants that operate at salinities of 10,000 to 20,000 ppm. The salinity of saltwater desalination plants ranges from 20,000 ppm to 20,000 ppm.

The increase in seawater salinity will increase the construction and operating costs of desalination plants due to plant component costs, as well as the rate of depreciation, maintenance, and chemicals required. Energy consumption and brine effluent are important challenges that should be well addressed.

13. Zero liquid discharge technology (ZLD)

The zero liquid discharge (ZLD) approach is one potential remedy for the brine disposal issues. One of the most alluring answers to the environmental problem with brine is to consider a Zero Liquid Discharge procedure. A solid layer of precipitate salts is the result of the ZLD process, which completely removes water from the reject brine stream. Brine will no longer be a threat to the environment thanks to Zero Liquid Discharge Desalination, and the process' recovery will be close to 100 %. ZLD has only been used in a small number of circumstances since it has long been seen to be an unprofitable option. However, the accelerating rate of population increase, the global water crisis, and the growing aware-

Table 2
Advantages and disadvantages of each technique.

Method	Advantage	Disadvantage
(MSF)	• Minimum required pretreatment. • Produced water with high quality. • High design capacity. • Cost is not depended on of salinity level.	• High level of technical knowledge. • Large capital investment. • Low recovery ratio. • Corrosion problems when using low quality materials. • Intensive energy needed.
(MED)	• Minimum required pretreatment. • Produced water with high quality. • Economics of large-scale capacity • Reliable with low required operational staff	• Large capital and operation cost. • Needed intensive energy. • High quality of using materials required to avoid Corrosion. • Before use the produced water needs to cooling and blending
(VC)	• Low capital and operation cost. • Economic with salinity more than 50000 mg/l. • Low energy requirement.	• High levels of maintenance needs for compressor. • Generating vapor needs additional heating source at start up. • Limited to small size plants.
RO	• Low energy requirement. • Low investment cost. simple and fast operation. • High production capacity. Cooling water not required.	• High cost of membrane and chemicals required. • Depend on quality of feeding water. • Pretreatment is adequately required. • Required a qualified staff.

Table 3
Percentage of RO desalination plant components.

Component	Percentage
High pressure pump	20 %
(RO) membranes and pressure vessels	15 %
High pressure joints	2 %
Control units	3 %
Design, construction and testing	5 %
Civil works	30 %
Intakes and Outfalls	10 %
Pretreatment and filters	15 %

Table 4
Cost of construction and operation for RO plants.

Investment cost	800–1200 dollars / m^3 / day
Energy consumption	3.5 kWh/m^3
Membranes	20 % / year (5 years)
chemicals	0.03 USD/m^3
Maintenance	2 % of investment cost/year
Employment	0.03 USD/m^3

ness of the need of environmental conservation have pushed this problem back into the spotlight.

ZLD technology works on brackish water with salinities less than 10000 ppm, and its efficiency increases with decreasing salinity, especially when RO desalination plants are used. A large water extraction rate is the main advantage of ZLD technology, but it has a negative environmental effect due to the ultra-saline effluent and the high cost of constructing two desalination plants, one working on brackish water and the other working on saline water.

Due to Egypt's anticipated brine salt output in 2025, ZLD method can be employed there to produce salt from effluent brine utilizing reverse osmosis desalination facilities. This method also demonstrates the viability from an economic standpoint of a novel brine treatment system to reduce the overall amount of brines produced and even achieve zero liquid discharge in desalination operations [36].

Reverse osmosis desalination facilities in Egypt might use the ZLD approach to produce water that is both environmentally friendly and economically feasible. However, greater focus has to be given to ZLD case studies in Egypt that employ actual economic models.

Judging the application of any new technology in any field should be from the technical side as well as economical. Lack of supporting data will result in misleading choice of the technology and consequently higher costs. Therefore, the following data should be available:

- The scientific reason and the economic feasibility of the desalination process.
- The brine disposal method, especially in high-productivity plants.
- The components of the desalination plants are produced.
- Percentage of the imported to local components in these plants.
- Water quality before and after.
- The construction costs of the plant per cubic meter.
- Operation and periodic maintenance costs per cubic meter.
- Technical and economic comparison of using new technology with existing technologies.

14. Desalination plants in Egypt

14.1. Existing desalination plants

The construction of 81 desalination plants with a total capacity of 913.69 $\times$ $10^3 m^3$/day was completed in the governorates of (North Sinai - South Sinai - Red Sea - Matrouh - Ismailia - Suez). The most important of which are the El Alamein desalination plant with a capacity of 150,000 m^3/day and El Galala desalination plant with a capacity of 150,000 m^3/day as shown in Table 5.

14.2. Desalination plants under construction

Eleven desalination plants with a total capacity of 465 $\times$ $10^3 m^3$/day are under construction in the governorates of (Matrouh - Red Sea - North Sinai - South Sinai - Port Said - Dakahlia - Alexandria - Suez). The most important of which are the East Port Said desalination plant with a capacity of 150,000 m^3/day and the Al-Arish and Sheikh Zuweid desalination plant with a capacity of 100,000 m^3/day as shown in Table 6.

Therefore, Figs. 7 and 8 shows the distribution of existing and under construction plants in Egypt.

Table 5
Shows the distribution of existing desalination plants in the governorates.

Governorate	Number of desalination plants	Design capacity (m^3/day)
Matrouh	18	302,500
Red Sea	17	109,700
North Sinai	29	52,090
South Sinai	14	161,000
Ismailia	1	2400
Suez	2	286,000
Total	**81**	**913,690**

14.3. Strategic plan for desalination plant construction (2020–2050)

A strategic plan has been prepared to expand the establishment of seawater desalination plants to meet drinking water needs, divided into five-year plans extending from 2020 to 2050 to provide a total capacity of 6.4 million m^3/day. This plan contains 4 main pillars as follows: [19].

First pillar: providing water needs to solve the current problems and the future natural population increase for the existing communities (1.35 $\times$ $10^6 m^3$/day).

Table 6
Shows the desalination plants being under construction in the governorates.

Governorate	Number of desalination plants	Design capacity (m^3/day)
Matrouh	East Matrouh desalination plant	65,000
Port Said	West Port Said	20,000
	East Port Said	150,000
North Sinai	Desalination plant for El-Arish and Sheikh Zuweid cities	100,000
South Sinai	Nabq Phase Two	6000
Suez	Ain Sukhna Expansions	70,000
Alexandria	Marbella	2000
Dakahlia	New Mansoura	40,000
Red Sea	El Shalateen xpansions	6000
	Abu Ramad Expansions	3000
	Halayeb Expansions	3000

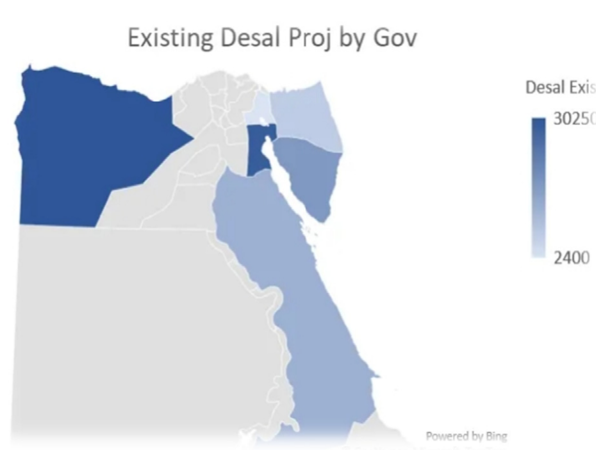

Fig. 7. For existing Desal. plants.

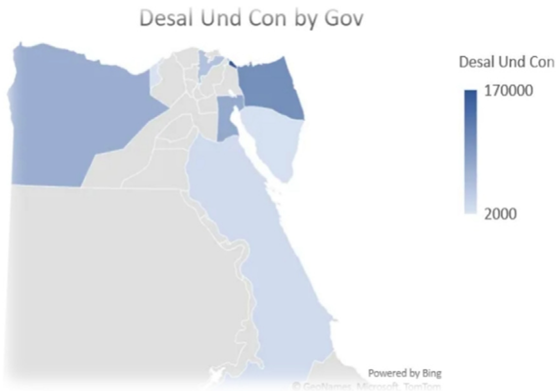

Fig. 8. For under construction Desal. plants.

Second pillar: Providing alternative water needs to stop the drinking water transfer to costal governorates (Matrouh - Red Sea - Sinai) (335 × $10^3 m^3$/day).

Third pillar: Providing alternative water needs for surface water (expansions - existing stations) (3.75 × $10^6 m^3$/day).

Fourth pillar: Providing the water needs required for urban development (approximately-one million m^3/day).

The first five-year plan (2020–2025) covers the construction of desalination plants with a total capacity of 2,942 × $10^6 m^3$/day in the governorates of (Matrouh - Red Sea - South Sinai - Ismailia - Port Said - Suez - Dakahlia - Kafr El Sheikh - Beheira).

15. Summary

Due to a lack of available freshwater resources, population growth, and industrial needs, Egypt's fresh water supply needs are growing, necessitating the use of alternate water sources other than the Nile River. Desalination has the potential to significantly increase Egypt's fresh water supply. Desalination of seawater is the process of removing salt and other dissolved particles to produce water appropriate for human consumption, agriculture, and industrial applications. Desalination applies to brackish water, such as agricultural and industrial waters, as well as marine and ocean water. Desalination is used in approximately 150 countries serving 300 million people.

More than 100 years ago, Egypt started to begin desalination to produce freshwater for domestic use in areas far from the public water supply network. Many desalination techniques are used to produce fresh water; thermal desalination techniques, such as MSF, MED, and VC; and membrane desalination techniques, such as RO, FO, and electro dialysis. The use of any technique depends on the plant capacity, the energy required, and the need for pretreatment.

The (RO) seawater desalination technique is the most used technique in the world and has approximately 70 % of the desalination capacity around the world. The Egyptian government constructed 81 desalination plants with a total capacity of 913.69 × $10^3 m^3$/day in the governorates of (North Sinai - South Sinai - Red Sea - Matrouh - Ismailia – Suez, such as El Alamein and El Galala desalination plants with a capacity for each of 150,000 m^3/day.

Additionally, eleven desalination plants are under construction with a total capacity of 465 × $10^3 m^3$/day (Matrouh - Red Sea - North Sinai - South Sinai - Port Said - Dakahlia - Alexandria - Suez). The most important of which are the East Port Said desalination plant with a capacity of 150,000 m^3/day and the Al-Arish and Sheikh Zuweid desalination plant with a capacity of 100,000 m^3/day.

Egypt has 6 five-year strategic plans extending from 2020 to 2050 for expanding seawater desalination plant construction to provide drinking water needs with a total capacity of 6.4 × $10^6 m^3$/day.

16. Conclusions and recommendations

Due to the population growth in Egypt and the increase in water needs, desalination is the best way to obtain additional water resources. The RO desalination technique is the best method in Egypt because of its low required energy, low investment cost, simple operation, and high production capacity. All coastal cities in Egypt should depend on desalinated seawater to avoid the high cost of surface water transfer. The environmental impact of brine effluent on marine life and eco systems should be taken into consideration. Now, EEAA requests a full EIA study before the construction of any desalination plant components. Physical and numerical analyses of brine outfalls should be established to study the near-field and far-field mixing zones. The Egyptian government should have a unified design approach (equations and charts) for brine disposal to the sea.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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