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The iWater Index: A Desalination-Sensitive Framework for Water Security and Resilience with Applications in Egypt

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Abstract

Water scarcity represents an increasing threat to sustainable development, particularly in arid and semi-arid nations such as Egypt. Desalination has emerged as a principal alternative to increase water supply. This paper introduces a new framework, complemented by the iWater Index, a novel holistic evaluation tool designed to quantify desalination's contribution to water security and resilience. The new DECSI framework integrates five interconnected dimensions—Drinking Water and Human Needs, Ecosystem Sustainability, Climate Resilience, Socio-Economic Equity, and Institutional and Governance Capacity—operationalized through 31 indicators spanning technical performance, environmental sustainability, social acceptability, economic feasibility, and governance effectiveness. The framework was illustrated for Egypt to qualitatively assess the current performance and strategic priority of each indicator. Results highlight the approximately intermediate performance along most axes, with climate resilience being a primary gap, indicating a challenge in reinforcing overall water resilience. The DECSI-iWater tool provides diagnostic and decision-support capabilities, enabling prioritization of interventions, the identification of critical gaps, and the formulation of a step-by-step roadmap for the integration of desalination into national agendas for sustainable water security and resilience. Although developed in Egypt, the model is designed for use in any geographic, institutional, and socio-economic setting, offering a globally relevant strategy for integrating desalination planning with robust water security objectives.

Keywords: desalination; DECSI framework; ecosystem sustainability; water security; Egypt

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1. Introduction

Water scarcity is one of the most alarming transboundary risks in the 21st century, with global implications for environmental sustainability, economic development, and social equity. According to a United Nations report in 2022, water scarcity affects 40% of the global population, with more severe situations found in developing countries. Many worldwide arid and semi-arid countries such as Egypt, North Africa, and Central Asia are particularly vulnerable to droughts, climate change impacts, and other water security problems [1]. On this basis, desalination is a feasible option for alleviating water scarcity, particularly in regions where conventional freshwater resources are limited. Moreover, water security in urban areas can only be achieved if the enhancement of desalination capacity is accompanied by efficiency gains in water distribution. High levels of non-revenue water due to leakages and water distribution inefficiencies will result in increased effective demand for desalination.

Many countries worldwide depend on desalinated water for over half of their domestic use to meet urgent industrial and drinking water needs and ensure long-term sustainability [2,3]. Over 95 million m^3 of desalinated water is generated every day by approximately 16,000 to 21,000 desalination facilities distributed across 177 countries worldwide. This highlights the global scale and strategic importance of this technology in the challenging situation of water scarcity [4]. Egypt, as a hyper-arid country, is dependent on the Nile River as a main water source, meeting 93% of the country's demand [5]. The water problem in Egypt requires integrated, innovative, and region-specific solutions developed collaboratively by the scientific community and stakeholders in Egypt.

Desalination in Egypt can present an insightful solution by harnessing a plentiful but underutilized source of freshwater. It has emerged as a critical component of Egypt's future strategy to enhance water resilience, security and close the supply–demand gap. It started by aiming to deliver drinking water to coastal and remote areas for petroleum and electricity company staff [6]. It can offer a new feasible and sustainable source of water in coastal areas such as tourism hubs along the Mediterranean and Red Seas and new Egyptian cities far from the Nile such as New Alamein, the New Administrative Capital, and Sinai. More than 90 desalination plants are running in Egypt, with a total capacity of 1.3×10^6 m^3. This offers a prospective solution away from the Nile water circumstances and climate effects affected by rainfall variability, droughts or upstream politics. In this regard, desalination has become a crucial component of the Egyptian National Water Resources Plan 2017–2027 [7]. However, integrating desalination into national water policies requires addressing its associated challenges including energy demands, environmental impacts, and high initial capital costs.

These factors necessitate a multi-dimensional approach that incorporates technical innovations, policy reforms, and economic incentives. Despite the rapid development in desalination worldwide, there is no unified set of desalination indices or a commonly applied framework to ascertain its contribution to urban water security. Existing methods are largely disjointed and context-specific, with indicator sets tailored to individual countries, regions, or even an individual desalination plant. For example, the bulk of research points to the technical and operational effectiveness of desalination, such as the energy efficiency and reliability of the system [4,8], whereas some mention environmental impacts, i.e., brine discharge and ecological stress [9]. Moreover, a set of other literature focuses on socio-economic aspects, particularly affordability and equity of access to desalinated water [10–12]. This highlights a gap in holistic evaluation approaches for desalination.

Furthermore, there has been limited exploration of how desalination contributes to global and regional efforts toward achieving water-related Sustainable Development Goals (SDGs), particularly in highly water-scarce countries like Egypt, where the challenge is existential. This gap motivates the development of the new DECSI–iWater framework, a novel desalination-sensitive index designed to capture the multi-dimensional contributions of desalination to water security and resilience. In the following context, five integrated dimensions of DECSI will be discussed: Drinking Water and Human Needs (D), Ecosystem Sustainability (E), Climate Change and Water-Related Hazards (C), Socio-Economic Equity (S), and Institutional and Governance Capacity (I). To the best of our knowledge, the proposed DECSI framework in this work is the first targeted approach that incorporates five interlinked dimensions discussing desalination, thereby standing out for its originality and added value.

Egypt was discussed as an illustrative case study, with the methodological contribution of this work lying in the transferable structure of the DECSI–iWater framework, which is applicable to a wide range of desalination-dependent urban systems. The Egypt case study relies partly on approximate values due to data scarcity; the outcome is representative

of a baseline which indicates the relevance of the framework in the field and also points out scope for enhancement through more accurate datasets in future research. While this study focuses on Egypt, the proposed DECSI-iWater framework can be adapted to other arid and semi-arid regions to evaluate multi-dimensional impacts of desalination on urban water security.

The DECSI-iWater framework seeks to address the following research questions:

- How can present and planned desalination infrastructures help satisfy Egypt's domestic water needs, particularly in water-stressed and crowded regions (D-framework)?
- How might desalination in Egypt affect the environment, particularly in terms of energy use, brine discharge, and marine biodiversity, and how can those negative effects be decreased in the long term to maintain the health of the water system (E-framework)?
- How might desalination strengthen Egypt's climate adaption strategies against water-related dangers such as droughts, sea-level rise, and high heat events (C-framework)?
- How equal is access to desalinated water across Egypt's socio-economic categories and regions? What measures are needed to increase affordability and inclusion (S-framework)?
- What are the primary governance, regulatory, and institutional hurdles to effectively integrating desalination into Egypt's national water strategy (I-framework)?

This study is built upon the Urban Water Security Assessment Framework developed by [13,14], which has been widely applied across diverse urban contexts to evaluate multi-dimensional aspects of water security, such as [15–18]. Accordingly, this study proposes the DECSI–iWater framework as a comprehensive, desalination-sensitive, and indicator-based tool that enables a holistic evaluation of desalination's contribution to urban water security and resilience.

2. Desalination and DECSI Framework

Desalination plants can significantly alter the physicochemical properties of adjacent water systems, for instance, by increasing salinity levels, changing temperature regimes, and discharging chemical residues [19]. Also, desalination plants may have negative effects on the whole ecosystem, climate resilience, equity, and governance structures. In this regard, the integrative framework (DECSI) will cover this topic by offering a structured and balanced method to assess the performance, sustainability, and long-term viability of desalination efforts in the Egyptian context. The DECSI framework aligns with Integrated Water Resources Management (IWRM) principles and global sustainability standards, including SDGs 6, 13, and 16. In the following context, the five integrated dimensions of DECSI will be discussed.

2.1. DECSI Dimensions

2.1.1. Drinking Water and Human Needs (D)

The foremost justification for the application of the desalination process lies in its potential to meet growing domestic water demand, especially under the circumstances of the current and future expected climate scenarios. In this regard, the population served as well as the water lost before reaching the consumer should be discussed. Desalination can also provide water to remote areas more cost-effectively compared to transporting freshwater over long distances. In this regard, the cost of desalinated water should be taken into consideration compared to its transportation cost. Also, as a result of the desalination process, a variety of known and emerging disinfection byproducts are formed in desalinated water, which affects its water quality and, consequently, public health [20]. D-dimension thus evaluates desalination's effectiveness in addressing basic human needs such as access

to safe and reliable drinking water with good water quality and low cost. Also, it takes into account continuous water supply availability and the expected interruptions.

2.1.2. Ecosystem Sustainability (E)

With the high trend of the desalination process and the increasing number of desalination plants, increased volumes of brine have been a cause of environmental concern due to harmful effects on essential ecosystems, such as groundwater or marine ecosystems [21,22]. In this regard, negative environmental drawbacks should be effectively treated to optimize the benefits of the whole desalination process and ensure long-term ecosystem sustainability. The outflow of the desalination plant, excluding the desalinated water, negatively affects the water characteristics of the nearby receiver water system. Also, the water temperature of the receiver system increases, which has high effects on different water quality characteristics. E-dimension is mainly focused on the environmental effects of the desalination process on the nearby marine system and its chemical pollution, as well as its energy consumption. A sustainable desalination process must consider such environmental effects while desalinating water.

2.1.3. Climate Change and Water-Related Hazards (C)

The main aim of this dimension is to focus on climate resilience, taking into consideration the expected risk exposures and adaptive capacity of desalination infrastructure to those exposures. Climate resilience means maintaining optimum function of desalination despite the adverse impacts of climate-related stressors such as preservation of the stable water supply in times of drought and flexibility in national water resource planning. Without proper precautions, desalination can itself be vulnerable to climate-induced risks, such as rising sea levels and extreme weather events that can damage infrastructure of the desalination plant or reduce system efficiency such as through storm surges, heatwaves, and sandstorms. Also, this dimension considers the water–energy nexus, as the desalination process can increase emissions of carbon if the desalination plant is powered by fossil fuel. This dimension thus prioritizes the role of desalination in supporting national climate change adaptation strategies while addressing its own exposure to climate risks.

2.1.4. Socio-Economic Equity (S)

The desalination process is more than just a technical concern; it also has financial issues that must be taken into consideration. Moreover, one of the main obstacles that hinder the desalination industry globally is the cost of its installation and operation, and the total cost of the production of desalinated water [23]. Different factors are well-thought-out to calculate the total cost of desalinated water, such as the cost of energy, the capacity of the desalination plant, the rate of water salinity, the type of desalination process, and the variables considered [23]. Consequently, this dimension discusses how desalination projects and their cost affect social inclusion, regional equity, and economic opportunity, especially for vulnerable or underserved populations. Different indicators are discussed, such as the affordability of desalinated water for average households, the national budget, and private sector participation. Also, this dimension discusses how water is delivered to different areas of rural, urban, and poor or rich regions. Further, this dimension discusses the level of community knowledge, acceptance, and trust in the desalination process as a water source. Moreover, it discusses two other different parameters of job creation and local economic development. Therefore, this dimension focuses on how desalination influences social equity to ensure that access to safe water is both affordable and inclusive.

2.1.5. Institutional and Governance Capacity (I)

Brine management is a complex challenge often requiring coordination across multiple actors and procedures [24]. The existing literature on brine management is highly concentrated on technical innovations, while neglecting the institutional dimensions necessary for scaling and sustaining these solutions [24]. The success of any desalination strategy does not depend only on its technical issues. It hinges on effective institutions, robust governance, and coordinated policymaking. Different laws and regulations should be firmly and innovatively applied to all stakeholders. This domain captures both the structural and functional aspects of governance, offering a multi-faceted perspective on institutional performance. UNDP (2014) [25] discussed the Policy Coherence Index, which analyses the degree of synchronization between the desalination process and other essential policy areas, such as water, climate, and energy, ensuring the necessity of comprehensive planning. Moreover, this domain discusses the effectiveness of Public–Private Partnerships (PPPs) through performance metrics related to timeliness and cost control [26]. Further, stakeholder participation levels gauge the inclusivity of governance processes by measuring civil society and private sector involvement. Furthermore, this dimension discusses the availability and quality of public reporting on desalination operations. Ultimately, this element emphasizes the importance of the frameworks of governance, institutional capacity, and transparent reporting for the sustainable uptake of desalination in national water policies.

2.2. Indicator Selection

A total of 31 indicators for the five core dimensions of DECSI framework were discussed, as shown in the next section. Each of the five DECSI dimensions includes a set of 6 or 7 indicators that provide together a nuanced knowledge of the effects and performance of desalination. Three main criteria guided the selection of the 31 indicators: relevance, complementarity, and measurability. Firstly, each indicator was selected based on how well it aligned with core goals for solving the water scarcity problem, especially in arid countries like Egypt. The indicators were designed to complement each other, avoiding redundancy and ensuring a holistic picture of the desalination system. Moreover, indicators should be easily measured or can be calculated using existing databases, scientific literature, government reports, or expert judgment. In this regard, we can ensure that the suggested framework is practical and applicable, especially in countries such as Egypt, where consistent and precise environmental monitoring may be limited or fragmented.

Considering the three criteria while discussing the desalination process from all five dimensions can offer a multi-criteria evaluation that allows stakeholders, planners, and politicians to prioritize investments, identify trade-offs, and match desalination initiatives with more general sustainability and governance objectives. Of these three requirements, the DECSI framework is guaranteed to be both practical and applicable even in situations where frequent monitoring of the environment is limited. Individually, the selected indicators provide a robust foundation for the multi-dimensional assessment set out in the ensuing section.

3. Methodology and Case Study Design

3.1. DECSI Framework and Its Indicators

The operational definition of water security adopted in this study is the capability of the country to have enough volume and acceptable quality to satisfy human and ecosystem needs and to be resilient to threats related to water. Under this definition, desalination is considered one of the main items in the portfolio of water options for Egypt, while the

31 proposed indicators are designed with an explicit relation to link the performance of desalination with the identified dimensions of water security.

The iWater Index is devised as a composite, multi-dimensional tool for water security assessment with specific sensitivity to desalination contexts. The theory about iWater valuation is based on a composite indicator that provides a way to reduce complex multi-dimensional knowledge into a cohesive, assessable score. The main goal is to allow for the assessment of desalination plants but also for their role within a water security system as a unit within a larger system that has been considered for its dimensions using DECSI. It synthesizes performance across the five key dimensions of DECSI framework. The selection of indicators and aggregation procedures was guided by the OECD Composite Indicator Handbook [27], established practices in water security indices [13,14], and best practice in sustainability assessment.

A methodological framework for assessing desalination in Egypt using the DECSI framework is shown in Figure 1. Step 1 involves understanding the desalination landscape and identifying the current capacity, water demand, key actors, and infrastructure gaps. Step 2 links desalination planning to DECSI's multi-dimensional context. Step 3 engages stakeholders in mapping the DECSI framework, while step 4 discusses the definition of appropriate indicators and data, enabling a structured evaluation of each dimension. Next, step 5 focuses on data integration and normalization followed by the final stage, in which the DECSI outputs are analyzed to support sustainable desalination strategies and inform decision-making. This framework facilitates a comprehensive, data-driven approach to managing desalination efforts in Egypt.

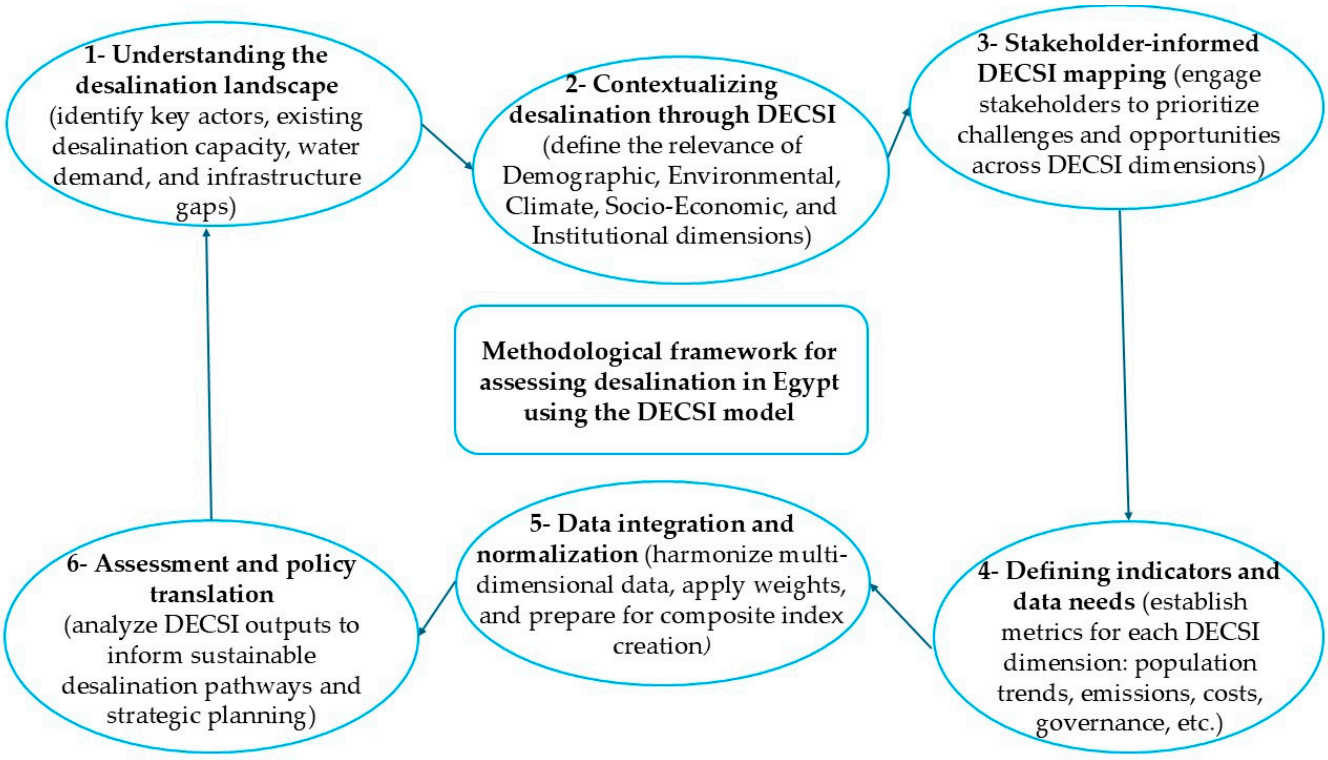

Figure 1. Methodological framework for accessing desalination in Egypt using the DECSI model.

Based on Aboelnga 2021 [18], the selection of indicators was guided by their ability to characterize the consequences of impacts on the affected entities, referred to as External Impact Receivers (EIRs). This was operationalized using a Process Analysis Method (PAM), which systematically links desalination pressures to their impacts across the urban water security dimensions and corresponding receptors. Aboelnga 2021 [18] discussed the DECS

framework only. In this regard, we added the I-dimension in our framework, as shown in Figure 2. This approach ensures transparency and traceability in the indicator selection process and allows for the consistent integration of technical, environmental, socio-economic, and governance aspects within the DECSI framework. The resulting indicators therefore represent measurable parameters capturing both the direct and indirect magnitude, extent, and significance of impacts on environmental, social, and economic receptors.

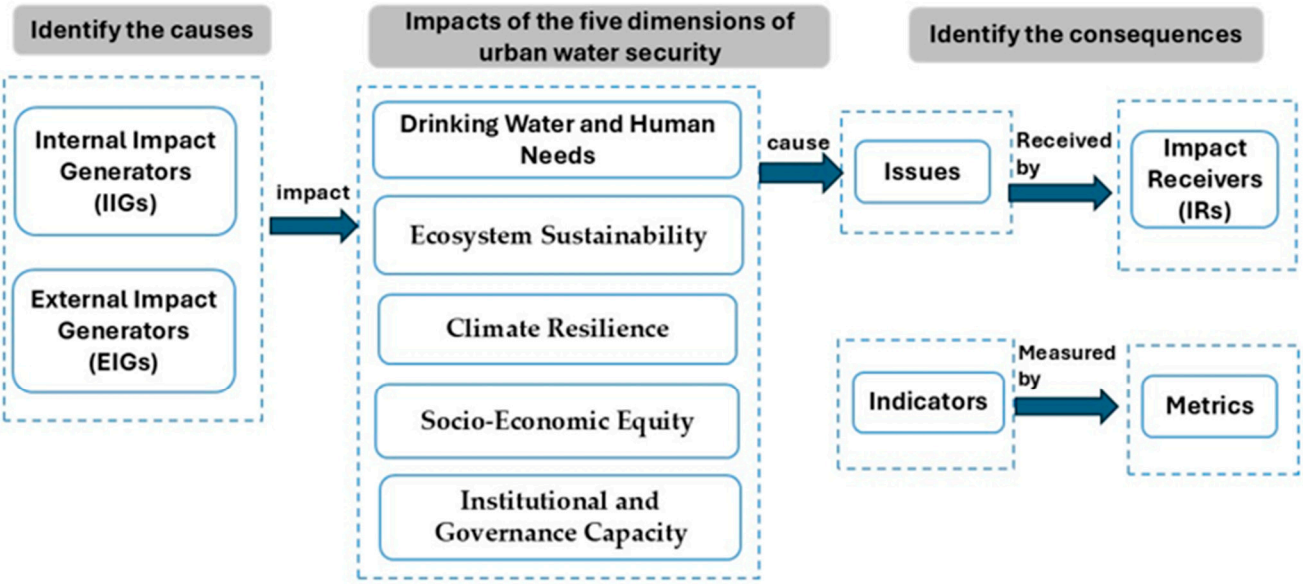

Figure 2. Process analysis method (PAM) of selecting indicators to measure urban water security.

As discussed in Section 2.1, the desalination process is not only considered a technical problem but should also be discussed from other different prospects across the five DECSI dimensions. Tables 1–5 show different indicators suggested in each dimension, references, definitions, and their measurement methods. The indicators shown in Tables 1–5 were designed by the authors as a result of a comprehensive review in the scientific literature, as well as professional judgment, and are customized for the desalination projects context. These indicators provide the foundation for applying the DECSI–iWater approach in the study. Also, Figure 3 shows the DECSI framework and its 31 indicators. A few of the parameters would capture interdependency (e.g., energy usage and carbon footprint) but were minimized to maintain wholesome coverage along environmental, technical, as well as climate perspectives. In this way, the framework can detect both indirect and direct effects of desalination. While empirical testing for validity and inter-rater reliability was beyond the scope of this research, the indicators were adapted and refined from prevailing international guidelines (e.g., Refs. [13,27] to ensure greater relevance and applicability to the Egyptian context.

To operationalize the DECSI-iWater framework, each of the indicators was rated on a five-point ordinal scale depending on its current status and performance level within the Egyptian desalination context. Scores range from 1 (weak), 2 (low–moderate), 3 (moderate), 4 (moderate–strong), to 5 (strong). Qualitative indicators were assessed on the basis of a systematic review of monitoring reports, peer-reviewed reports, and government statistics, with expert judgment added as necessary. Where quantitative data were available, thresholds were added directly onto the 1–5 scale (e.g., rates of compliance, rates of service coverage, or emissions reduction targets).

Calculations of the iWater score follow a structured composite indicator approach. Firstly, all indicator values were standardized using a five-point ordinal scale, ensuring comparability across dimensions. Dimension scores were approximated by the arithmetic

mean of the indicator ratings standardized by each dimension. Equal weighting was given to all the dimensions to ensure transparency and comparability. This choice is in accordance with the Organization for Economic Co-operation and Development (OECD) Composite Indicator Handbook (2008) [27] suggestion because sufficient empirical evidence for differential weighting is not yet available, and expert opinion has not been established yet. Future refinements could explore differential weighting and sensitivity analysis, once sufficient expert consensus and empirical evidence become available.

Table 1. Six indicators considered in D-dimension, their definitions, references, and measurement methods.

No.	Indicator	Ref.	Definition	Measurement Method
P1	% Population Served by Desalinated Water	[28]	Proportion of total population receiving desalinated water	(No. served by desalinated water/Total population) × 100
P2	Frequency of Supply Interruptions	[29]	Number of unscheduled interruptions in water supply per year	Count interruptions per year per service area
P3	Drinking Water Quality (WHO/Egyptian Standards)	[30]	Levels of key contaminants (TDS, pathogens, heavy metals) compared to standards	Water sampling and lab testing for TDS (mg/L), coliform counts
P4	Cost per m^3 for Households	[31]	Average consumer cost of desalinated water per cubic meter	Total household water bills/Total volume consumed
P5	Non-Revenue Water (NRW) in Distributed Network	[32]	Percentage of produced water lost before consumption	(Volume of water lost/Volume produced) × 100; detected by metering and audits
P6	System Reliability (Continuity of Service)	[33]	A percentage of total hours per year water supply is available	(Hours of supply available/Total hours in year) × 100

Table 2. Six indicators considered in E-dimension, their definitions, references, and measurement methods.

No.	Indicator	Ref.	Definition	Measurement Method
P7	Brine Management and Disposal Compliance Index	[9]	Degree of compliance with environmental regulations for brine discharge	% of plants following legal discharge standards (monitored via inspections) of the total number of desalination plants
P8	Marine Water Quality and Biodiversity Index	[34]	Measure of desalination impact on local marine species and habitat health	Biodiversity surveys pre/post plant operation, species richness, abundance, and water-quality indicators (e.g., salinity, DO, temperature), aligned with UNEP (2019) [35] marine monitoring guideline
P9	Energy Use per m^3	[8]	Energy consumption required to produce one cubic meter of desalinated water	Total kWh consumed/Total m^3 desalinated
P10	Carbon Footprint of Desalination	[36]	Total greenhouse gas emissions (CO_2-eq) per m^3 desalinated water	Life Cycle Assessment (LCA) including energy sources
P11	Use of Renewable Energy	[37]	Percentage of energy used for desalination derived from renewable sources	(Renewable energy consumed/Total energy consumed) × 100
P12	Chemical Usage Intensity	[9]	Amount of chemicals used in desalination per m^3 (e.g., anti-scalants, cleaning agents)	kg of chemicals used/m^3 produced

Even though some of the indicators may appear to be interrelated (e.g., energy use, emissions, and carbon footprint), they were intentionally retained to capture different

dimensions (operational efficiency, direct environmental impact, and full life-cycle analysis). Similarly, the same service indicators such as interruptions and reliability measure complementary aspects of performance. This gives a holistic rather than reductionist view of the contribution of desalination to water security.

Table 3. Six indicators considered in C-dimension, their definitions, references, and measurement methods.

No.	Indicator	Ref.	Definition	Measurement Method
P13	GHG Emissions per m^3	[36]	Greenhouse gases emitted per cubic meter of water produced	LCA carbon footprint analysis in kg CO_2-eq/m^3
P14	Desalination Dependency Ratio	[38]	Proportion of total water demand met by desalination	(Volume from desalination/Total water demand) × 100
P15	Plant Vulnerability to Sea-Level Rise	[36]	Assessment of physical risk from rising sea levels and flooding	Risk assessment using sea-level rise projections and plant location
P16	Integration with Disaster Risk Reduction (DRR) Plans	[39]	Degree to which desalination is included in local/national DRR strategies	Qualitative policy analysis, % of DRR plans incorporating desalination
P17	Adaptive Management Capacity	[40,41]	Ability of operators to respond to climate variability and hazards	Presence of adaptive protocols, emergency response plans
P18	Water Source Resilience	[34]	Stability of source water salinity and availability amid climate impacts	Monitoring variability of feed water quality over time

Table 4. Seven indicators considered in S-dimension, their definitions, references, and measurement methods.

No.	Indicator	Ref.	Definition	Measurement Method
P19	Affordability Index across Income Groups	[31]	Affordability of desalinated water for different household income groups (low, middle, high), reflecting cost burden	$\sum$(Average desalination water tariff/household income) × 100 for all income groups
P20	Public Investment and Subsidy Share in Desalination Financing	[42]	Share of government budget dedicated to financing desalination projects and infrastructure	(National desalination budget/ Total water sector budget) × 100; budget documents analysis
P21	Extend of Private–Public Partnerships (PPP) in Desalination	[43,44]	Proportion of desalination capacity delivered or financed via PPP models	(Capacity under PPP/Total desalination capacity) × 100; project databases, reports
P22	Regional Equity in Access to Desalinated Water	[45]	Degree of disparity in access to desalinated water across urban vs. rural and rich vs. poor regions	Statistical analysis of % population served by region; Gini coefficient of access; comparison of urban vs. rural coverage.
P23	Regional Economic Impact/Job Creation Index	[46]	Measures the regional economic impact of desalination plants through direct and indirect employment and share of local workforce	Labor surveys, company employment records
P24	Public Awareness and Social Acceptance of Desalination	[43]	Level of community knowledge, acceptance, and trust in desalination process as a water source	Structured community surveys, focus groups, media analysis
P25	Life Cycle Cost Analysis per m^3 of Water (LCCA)	[47]	Total cost of a desalination plant over its lifetime (capital, operation and maintenance, replacement, disposal) divided by total water produce	LCCA, expressed in USD/m^3

Table 5. Six indicators considered in I-dimension, their definitions, references, and measurement methods.

No.	Indicator	Ref.	Definition	Measurement Method
P26	Number and Coordination of Agencies Involved	[48]	Count of governmental and non-governmental bodies in desalination governance	Document analysis of official roles; coordination index based on overlap/clarity of mandates
P27	Policy Coherence Index	[37]	Extent of alignment between desalination and water/energy/climate policies	Qualitative policy analysis with scoring system
P28	Private–Public Partnership (PPP) Performance	[43]	Effectiveness of PPPs in project delivery and management	Performance metrics: on-time delivery, cost control supplemented by stakeholder satisfaction survey
P29	Regulatory Compliance Rate	[30]	% of desalination plants adhering to environmental and health regulations	Regulatory inspections and reports
P30	Stakeholder Participation Level	[49]	Degree of involvement of civil society and private sector in decision-making	Number and diversity of stakeholder consultations per year; inclusiveness scoring (government, private, community).
P31	Transparency and Reporting Quality	[50]	Extent to which desalination operations are publicly reported in an accessible, timely, and comprehensive manner.	Content analysis of reports, open data portal availability, reporting frequency.

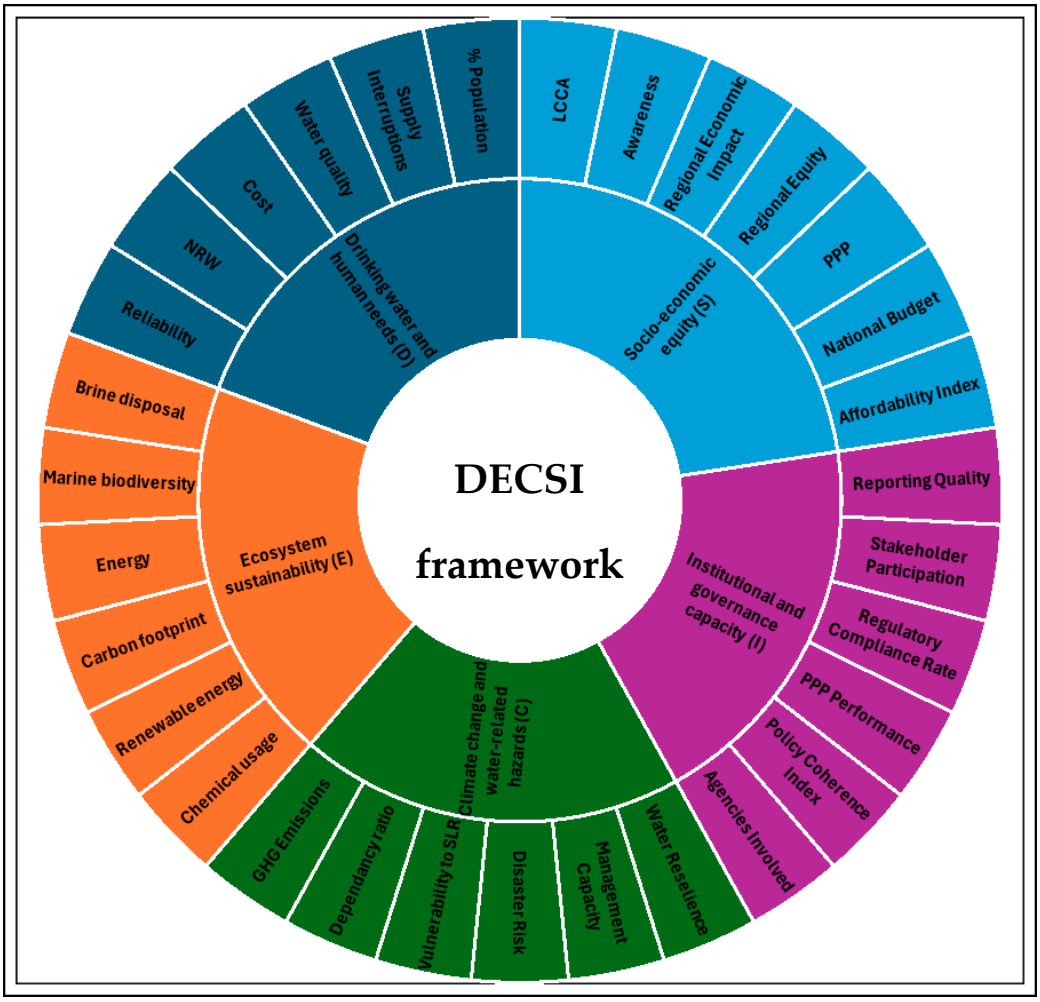

Figure 3. DECSI framework and its 31 indicators.

Together, these indicators provide a structured tool to assess desalination performance across technical, environmental, social, and governance perspectives. Where field data are scarce, proxy estimates from official reports and expert judgment are applied, with explicit recognition of associated uncertainty. Tables 1–5 detail the indicators, their references, their definitions, and methods of measurement.

3.2. Case Study of Egypt

More than 100 years ago, the desalination process began in Egypt with the limited purpose of delivering drinking water to coastal and remote areas, in which workers in petroleum and electricity live [6]. The number of desalination plants in Egypt has increased dramatically in the past decade, aiming to present a solution for water scarcity and relieving stress on the main source of water of the Nile River in Egypt. Due to its highly increasing population growth and climate effects, Egypt was chosen in this work to be the first application of the DECSI framework in a trial to build a comprehensive picture of the desalination process. Desalination facilities in Egypt's coastal zones are divided into numerous geographical regions: West, Central and Eastern North Coast, Suez Canal and Gulf of Suez, south Sinai and the Red Sea governorate.

Based on different sources of governmental data, a clear rise in desalination trends after 2017 with approximately 75% of the total desalination plants was noticed, especially along the Red Sea and Eastern North Coast, implying new policy or funding initiatives. Also, Egypt has expanded its desalination plants to 125 plants with a total capacity of 1.31 million m^3/day, as of early 2025. Table 6 shows the different zones described, their average capital cost per cubic meter of desalinated water, the capacity of desalinated water in m^3 per day and a comment on the high or low cost of desalination in each study zone. Those data were obtained from reports from Ministry of Housing and Infrastructure. We can find from the table that the average capital cost ranges from 716 USD in Zone I, West-North Coast, to 1264 USD in Zone II, Central-North Coast. This means that site selection, excessive nutrient runoff and transport of pollutants and heavy metals are all parameters that contribute to higher effects of the cost of desalinated water. Also, we can see that Zone II, Central-North Coast, has the highest average capacity of 95,000 m^3/day, with a capacity ranging from 40,000–160,000 m^3/day indicating large-scale and high-cost operations. The characteristics of these six zones provide the empirical foundation for applying the DECSI framework in Egypt, as presented in the next section.

Table 6. Different zones of desalination plants showing the average capital cost per cubic meter of desalinated water and capacity range of cubic meters per day, with average capacities and comments on the data.

Zone	Av. Capital Cost per m^3	Capacity Range m^3/day	Av. Capacity m^3/day	Comment
Zone I: West-North Coast	716 USD	500–40,000	9500	This zone presents minimal constraints for desalination plant site selection and availability, and utilizes high-quality water resources. This would have a substantial positive impact on the capital cost.
Zone II: Central-North Coast	1264 USD	40,000–160,000	95,000	Situated within the Nile Delta, the Mediterranean Sea faces the 'Delta effect' in this zone. This encompasses excessive nutrient runoff from agricultural and urban sources, along with the transport of pollutants like heavy metals, pesticides, and industrial waste into the marine environment. Consequently, Desalination Water Treatment Plants (DWTPs) must implement specific measures to ensure both water quality and the longevity of their equipment, particularly the critical membranes.

Table 6. *Cont.*

Zone	Av. Capital Cost per m^3	Capacity Range m^3/day	Av. Capacity m^3/day	Comment
Zone III: East-North Coast	985 USD	5000–100,000	15,000	While this zone shares certain characteristics with Zone (I), such as distance from the 'Delta effect' and coastal land availability, the relatively higher construction costs in this area may be attributed to potential lower source-water quality. This could be influenced by proximity to a 'Bardawil lake' and the adjacency of the Gaza Strip, which experiences high human activity and inadequate wastewater management infrastructure in a very limited area; therefore Zone (II) is vulnerable to fluctuations in water quality based on the sea currents.
Zone IV: Suez Canal and Gulf of Suez	893 USD	2000–136,000	89,500	Normal average
Zone V: Red-Sea Governorate	1000 USD	N/A	8750	The selection of suitable sites for desalination plants in these zones requires careful consideration due to several factors where the sensitivity of the surrounding ecosystems, particularly coral reefs and mangrove habitats, could be significantly impacted. This necessitates specific designs for both seawater intake and brine discharge structures to minimize harm. Furthermore, the low population density and scattered nature of communities in these zones can lead to increased capital costs. The need for numerous water production sites to serve these dispersed communities necessitates the construction of multiple facilities, further impacting overall project expense.
Zone VI: South Sinai	1002 USD	N/A	10,500	

Regarding water demand, the main use of desalinated water in the Egyptian environment is for municipal consumption in coastal towns and tourist establishments. The issue of affordability for desalinated water is one of the main issues affecting its use, especially in the domestic sector, due to high costs of production associated with this water. The mentioned socio-economic factors affect the location and role of desalination initiatives in improving access to water resources.

3.3. Application of DECSI Framework to a Case Study of Egypt

In this paper, the DECSI framework is applied to a case study of Egypt as a hyper-arid country to evaluate its sustainability indicators. To each indicator described in Sections 2 and 3, related data are compiled and reviewed. Current performance is qualitatively evaluated by three descriptive levels (weak–moderate–strong) to provide an open presentation of Egypt's standing. For clarity in presentation, the results in Tables 7–11 are shown using a simplified three-level scale (Weak–Moderate–Strong) by merging the intermediate levels of the original five-point ordinal scale. However, all computations, including the average scores for each DECSI dimension, were based on the full five-point scale, ensuring accuracy and preserving detail in the quantitative analysis.

Additionally, the relative importance of each of the indicators is highlighted by qualitative assessment rather than numerical ordering, such that their strategic significance is realized without the use of discretionary weights. The two-sided approach works to report both the current conditions and the areas of priority for sustainable water management in Egypt while accounting for available data constraints.

Table 7. Six indicators considered in the D-dimension, their performance (weak–moderate–strong), and comments from review and available data on both performance and importance of each indicator.

No.	Indicator	Per.	Comment on Performance Rate from Available Data	Comment on Importance from Review
P1	% Population Served by Desalinated Water	Weak	Desalination in Egypt still serves a very low percentage of the population in Egypt (approximately less than 2 million people from 110 million) concentrated mainly in coastal areas and remote areas from the Nile River.	Very critical for assessing national water security, especially in coastal and urban areas in such hyper-arid country.
P2	Frequency of Supply Interruptions	Moderate	Different technical issues can result in shutdowns of some desalination plants, especially in developing countries such as mischaracterization of feedwater, inadequate maintenance, and inappropriate design. Extended outages reported in Red Sea governorate in 2024.	Interruptions directly affect reliability and public trust. Such interruptions can also lead to reduced plant lifespans and high operating expenses. Its importance will increase with the increase in dependency on water desalination.
P3	Drinking Water Quality (WHO/Egyptian Standards)	Strong	71% and 100% of desalination plants had excellent water rank according to the standard limits of the World Health Organization (WHO) and the Egyptian Water Quality Standard, respectively [51].	Water quality is central to public health and acceptance.
P4	Cost per m^3 for Households	Moderate	Average cost of desalination for 1 m^3 of seawater ranges from 0.7 to 0.9 USD. While average cost of producing 1 m^3 of global desalinated water ranges from 0.5 USD for large plants, to more than 1.25 USD for smaller plants [52]. So, the performance rate of Egypt considering P4 parameter could be considered moderate.	Very important parameter, especially in developing countries. Cost directly impacts equity and willingness to pay.
P5	Non-Revenue Water (NRW) in Distributed Network	Moderate	Developing countries account for one-third of global water utility losses due to non-revenue water. Also, leaks and inefficiencies in networks are expected. Egypt's average has NRW exceeding 40% [53].	It is an important parameter, but it is a general parameter to water distribution networks not specifically related to desalination plants.
P6	System Reliability (Continuity of Service)	Moderate	Better technology and planning, especially for new plants, promote good reliability, while old plants may show some operational disruptions, especially with untrained technical staff. Also, other operational, technical, and infrastructure issues persist.	Water resources should be consistently available, especially in water-scarce regions. The importance of this parameter will increase with increasing the dependency on desalinated water and the increased water security problems.

Table 8. Six indicators considered in the E-dimension, their performance (weak–moderate–strong), and comments from review and available data on both performance and importance of each indicator.

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P7	Brine Management and Disposal Compliance Index	Moderate	Uncontrolled disposal of the brine can have serious environmental impacts, particularly on marine ecosystems. The Egyptian Environmental Affairs Agency nowadays requests a full environmental impact assessment study before the construction of any desalination plant components [6]. This consideration may be reducing effects of brine disposal on nearby water systems. According to reports, not all plants completely follow the rules for treating effluent or disposing of brine.	Brine plumes typically increase salinity, chlorine, and heavy metals in the receiving water body, which may cause cumulative ecological effects if multiple plants discharge in the same coastal zone [54]. While it is important to study effects of brine disposals and their harm to the nearby ecosystem, it may not receive as much attention compared to affordability, supply reliability, and energy use in Egypt. The situation is expected to change in the upcoming decades.
P8	Marine Water Quality and Biodiversity Index	Moderate	No national biodiversity monitoring framework or firm regulations are fully integrated with desalination development. Also, as mentioned previously, not all plants completely follow the rules for treating effluent or disposing of brine. Although the situation is moderate, it could worsen in the future, particularly in the case of absence of strict regulations.	The nearby coasts of the desalination plants can be highly polluted with brine discharge with high contents of salinity, chlorine, and heavy metals. Egypt's coasts of the Red Sea and its coral reefs and the Mediterranean Sea with key fish nurseries can be highly affected, in which both coasts are vital for ecological reasons, tourism income, and socio-economic effects.
P9	Energy Use per m^3	Moderate	Reverse osmosis (RO) is the dominant desalination technology worldwide and in Egypt [6]. While RO has lower electricity consumption compared to thermal desalination processes, its energy demand remains considerable, particularly when powered by conventional energy sources. In Egypt, RO desalination typically consumes 3.5–5.5 kWh/m^3, indicating moderate energy performance.	Very important parameter for the following reasons: - Cost issues - Pressure on Egypt's electricity - Increase of carbon emissions
P10	Carbon Footprint of Desalination	Moderate	It is defined as the sum of individual greenhouse gas emissions such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). They are converted to carbon dioxide equivalent (CO_2eq) by converting CH_4 and N_2O emissions using their global warming potential [55,56]. Globally, carbon footprints from desalination typically range from 0.4 to 6.7 kg CO_2/m^3 using RO technology, which produces low quantities of CO_2 when compared to other technologies [57]. According to government plans, all new desalination plants shall be powered by renewable energy, thereby reducing their carbon footprint. Given Egypt's relatively modest installed capacity and the RO dominance, current footprints are moderate by international RO ranges; however, planned capacity additions mean footprints could rise without firm renewable energy integration.	Due to its negative effects such as: - Increased global warming - Increased sea-level rise - Increased carbon taxes or emissions trading penalties - Causes of air pollution and harmful emissions affecting public health. In this regard, it is essential to calculate the carbon footprint from desalination, which is very highly related to, for instance, wastewater treatment, especially with the increased trend toward desalination.

Table 8. *Cont.*

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P11	Use of Renewable Energy	Moderate	Egypt is rapidly moving in the direction of using renewables-powered desalination plants, from small resort-based systems such as Marsa Alam resort to large-scale systems. Dependence on renewable-powered desalination plants remains limited, but their large-scale projected expenditures are quickly moving toward wider implementation. For instance, Egypt is aiming to build 17 solar-powered planned desalination plants, supplying 2.8 million m^3/day. So, the percentage of solar-powered desalination plants is expected to increase from its current status of very few projects with small capacities.	Use of renewable energy can result in: - Low energy consumption - Low greenhouse gas emissions. - Low carbon footprint of desalination, serving to lessen the effects of climate change. - Reduce reliance on fossil fuels. - Provide greater reliability [58].
P12	Chemical Usage Intensity	Moderate	It is the mass of treatment chemicals required to produce 1 m^3 of desalinated water. Typical chemicals used are coagulants, antiscalants, chlorine or biocides pH adjusters, and others. In Egypt, chemical usage is likely to be moderate, affected by high salinity or turbidity in intake water from the Red Sea or Mediterranean Sea, conventional pretreatment methods and limited use of green or low-chemical technologies. Situation may be better in the future, especially in newer plants aiming for sustainable or low-impact operations.	Mishandled quantities of the chemical used in the desalination process can harm aquatic ecosystems or public safety and it is important to mitigate its risks by stricter monitoring and proper waste management practices, while chemical usage is often less visible or politically sensitive when compared to other parameters, reducing its pressure in public and policy discourse. Also, it can be managed with staff trainings and protocols. High chemical usage can: - Increase operational costs - Increase environmental pollution - Pose health and safety risks for workers and ecosystems.

Table 9. Six indicators considered in the C-dimension, their performance (weak–moderate–strong), and comments from review and available data on both performance and importance of each indicator.

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P13	GHG Emissions per m^3	Strong	Same as P10, as Egypt is not a global leader in the desalination sector and still has a low desalination capacity. Also, the trend toward using renewable energy in RO technique may help have low GHG emissions.	Important for discussing the efficiency of the desalination plant Helps in the selection of the applied technology (RO, MSF, or others) Helps in the selection of energy sources (renewable vs. fossil fuel). Helps stakeholders to discuss the water–energy nexus performance
P14	Desalination Dependency Ratio	Weak	Desalinated water provides not more than 5% of Egypt's national water demand. However, it offers a good solution for coastal areas away from the Nile in Matrouh, Sinai, and Red Sea governorates.	Although a very low percentage of the population in Egypt depends on desalinated water, it offers a good lifestyle, tourism activities, and economic visions in coastal cities away from the Nile.
P15	Plant Vulnerability to Sea-Level Rise	Weak	Egypt is rated among the most exposed countries to SLR impacts in low-lying coastal zones such as the Nile Delta and coastal zones [59–61]. So, this parameter was rated weak, which means low performance and a high risk of sea-level rise.	Important for the following issues: - Costly repairs or relocations - Operational downtimes - Ensuring sustainable infrastructure.

Table 9. *Cont.*

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P16	Integration with Disaster Risk Reduction (DRR) Plans	Weak	Great efforts are tending toward water desalination in Egypt to meet water demand, especially in coastal and new urban areas. However, concerns about DRR are still limited. Also, some environmental disasters such as earthquakes are not highly expected when compared to other highly probable disasters such as the faulty design of plant components [62]	Disasters facing the water sector in Egypt are unfortunately highly concentrated around desalination plants. For instance, the coasts of the Mediterranean Sea and the Red Sea are highly vulnerable to sea level rise and storm surges. Also, the Nile Delta is considered a highly vulnerable low-lying region.
P17	Adaptive Management Capacity	Weak	- Shortage of early warning systems for climate events - Few plans for climate contingencies - The desalination process is still growing and is not yet widespread enough to support resilience on scale.	Egypt is strongly expected to face different climate changes such as coastal flooding, extreme heat, and water source variability. Without adaptive capacity, systems may fail under pressure, leading to service interruptions or higher operating costs.
P18	Water Source Resilience	Moderate	Coasts of Egypt along the Red Sea and Mediterranean can provide regularly saline water sources. However, those coasts are highly and continue affected by climate change effects, which have negative effects on water source resilience, such as high sea level, saltwater intrusion and coastal erosion. Also, pollution, algal blooms, and sedimentation can affect water quality, especially near urban and industrial zones.	Water source resilience means that continuous water remains available all year with salinity within expected ranges and is not highly affected by climate effects and environmental factors. It is an important factor for the preservation of the desalination process with fewer interruptions and without extra stress from cost regarding high levels of salinity, high water temperature, or high pollution from factories and human effects.

Table 10. Seven indicators considered in the S-dimension, their performance (weak–moderate–strong), and comments from review and available data on both performance and importance of each indicator.

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P19	Affordability Index across Income Groups	Moderate	The average production cost of desalinated water in Egypt ranges between 0.7 and 0.9 USD/m^3, which is relatively high when compared to conventional Nile-based water supplies. While this cost remains manageable for higher-income households and specific coastal or touristic areas, it poses affordability challenges for low- and middle-income groups, particularly in the absence of targeted subsidy mechanisms. Accordingly, the affordability of desalinated water across income groups is assessed as moderate.	Very important parameter, especially in developing countries. Cost directly impacts equity and willingness to pay.
P20	Public Investment & Subsidy Share in Desalination Financing	Moderate	Egypt as an arid country is facing enormous water scarcity challenges, especially in the face of increasing population and climate change. So, increased national budget is being allocated to the construction of desalination plants. In 2022, Egypt had about 81 operational desalination plants, producing approximately 917,000 m^3/day while the number of desalination plants increased to reach 125 desalination plants in 2025 with a combined capacity of around 1.31 million m^3/day. This number shows the increasing concern toward desalinated water as an urgent solution to water scarcity problems.	- Reflects policy priority and Egypt's vision - Enables expansion away from the Nile - Critical for resilience - Shows commitment to SDGs

Table 10. *Cont.*

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P21	Extend of Private-Public Partnerships (PPP) in Desalination	Weak	In the past few years, Egypt has been pushing both the public and private sectors to investigate in desalination plant construction by applying different new techniques and technologies. Public–private partnerships (PPPs) have been promoted, especially under the Build–Operate–Transfer (BOT) model. However, institutional capacity and transparency remain challenges. To enable desalination expansion, a centralized and transparent regulatory framework is essential, along with clearly defined roles and accountability mechanisms across agencies.	Same as the parameter P20, it is an important parameter, as it can help expand away from the Nile Delta. It shows commitment to SDGs and reflects policy priority toward water desalination.
P22	Regional Equity in Access to Desalinated Water	Moderate	In Egypt, the idea of desalinated water is still related to coastal and remote areas away from Nile water. Most desalination plants are concentrated along the Red Sea, the Mediterranean Sea and Sinai. While Upper Egypt, for instance, does not use any desalinated water. In the future, the situation may worsen with the increase in water scarcity problems and needs from the desalination plant in the Nile delta may be a must.	It is important that all areas have access to clean water needed without any predilection according to tourism and income rate. Any inequality can lead to social tension or a lack of political and public support for desalination investments. Also, two SDGs are highly related to regional equity such as Goal 6 (Clean Water and Sanitation for all), and Goal 10 (Reduced Inequalities).
P23	Regional Economic Impact/Job Creation Index	Moderate	Desalination projects in Egypt generate limited direct and indirect employment, primarily in construction, operation, and maintenance activities concentrated in coastal regions. While the overall job creation potential remains modest compared to labor-intensive sectors such as agriculture, the ongoing expansion of desalination infrastructure contributes to localized economic activity. Accordingly, the regional economic and employment impact is assessed as moderate.	- The main goal is to address the problem of water scarcity and achieving sustainability goals, which are inherent in human existence. - Desalination plants aim to address water supply, not job creation. - Other sectors such as agriculture can provide more employment with lower skills - Concentrated desalination plants in coastal or remote areas with concentrated employment
P24	Public Awareness and Social Acceptance of Desalination	Moderate	- Most Egyptians are not aware of and cannot realize a tangible impact of desalination process - Limited visibility of desalination's benefits among most Egyptians cities - Desalination is perceived as a costly solution from a public perspective. However, limited public awareness does not translate into social rejection. There is no evidence of widespread public opposition to desalination in Egypt, and social acceptance is generally adequate in areas where desalinated water is already in use. Therefore, despite limited public awareness, this indicator is assessed as moderate.	Acceptance of the desalination process is vital, an important parameter in the progress of the process and presenting a prospective solution to water security. Especially during the growth phase of the desalination plants, public awareness is considered a top-tier issue. Without public awareness, mistrust will lead to false fears considering high cost and harmful effects on human health.
P25	Life Cycle Cost Analysis per m^3 of Water (LCCA)	Moderate	Life-cycle cost analysis (LCCA) per m^3 of desalinated water in Egypt shows substantial variability depending on technology, plant scale, and energy source. Literature and project estimates place LCCA roughly between 5 and 19 LE/m^3. Using pragmatic thresholds ($\leq$6 LE = Low; 6–12 LE = Moderate; >12 LE = High), the LCCA for most Egyptian applications falls within the Moderate–to-High range. We therefore classify the LCCA indicator in this study as 'Moderate' (pilot average), while noting that some small-scale or less-efficient projects register 'High' LCCA values.	High importance: provides comprehensive economic evaluation of desalination projects and compares alternatives

The process of identifying the indicators and assessing the performance of these indicators has been carried out by the authors with the aid of secondary data. Where specific data is unavailable, expert opinion has been incorporated. While involving stakeholders in the decision has been rendered difficult by the availability of data, this framework permits the engagement of various stakeholders.

Table 11. Six indicators considered in the I-dimension, their performance (weak–moderate–strong), and comments from review and available data on both performance and importance of each indicator.

No.	Indicator	Per.	Comment on Rate from Available Data	Comment on Importance from Review
P26	Number and Coordination of Agencies Involved	Moderate	Different governmental and non-governmental agencies are involved in the desalination sector in Egypt. For instance, Ministry of Housing, Ministry of Irrigation, Ministry of Environment and Holding Company for Water and Wastewater (HCWW) are examples of involved governmental agencies. While other non-governmental sectors involve the PPP sector and other international institutions. The moderate scale was concluded via high committee of water and water committee in each governorate.	The number of governmental, semi-governmental, and non-governmental agencies and their roles in planning, regulating, financing, operating, and managing desalination projects is considered a double-edged parameter. It can bring diverse expertise with good actions on sustainability and performance, while too many agencies with different opinions can show slow decision-making, overlapping mandates and regulatory confusion.
P27	Policy Coherence Index	Moderate	As mentioned in the P26 parameter, different governments and PPP are involved in the desalination process, which can lead to a coherent process. Egypt is also reviewing a strategic plan for seawater desalination projects until 2050. The DECSI framework can help increase the policy coherence across agencies.	The desalination process cannot stand alone, and it is highly related to different other sectors such as water, the environment, cost, health, and energy, which require a high coherence index. Fragmented planning of the desalination process can lead to inefficiencies, delays, and duplication in achieving of desalination main aim. While coherent policies lead to avoidance of water conflicts with energy or climate preservation.
P28	Private–Public Partnership (PPP) Performance	Moderate	As previously mentioned, Public–Private partnerships (PPPs) are being promoting in the past few years. For instance, Hurghada and Al-Arish desalination plants are already completed projects depending on the private sector. All projects through PPP are advancing quickly. This parameter may show more progress in the upcoming years.	1- Affect public trust 2- Quick advancement in the desalination process 3- Reduce public financial burden 4- Attract foreign investment 5- Future national strategy is largely built on PPP investments.
P29	Regulatory Compliance Rate	Moderate	From the previous mentioned information, newer, donor-funded, or military-managed plants typically have higher compliance rates than older, municipally managed ones.	Achieving regulatory compliance helps ensure satisfying levels of public health safety, environmental protection of vital coasts of the Red Sea and Mediterranean Sea, and trust issues encouraging private and foreign investment, while non-compliance can result in high levels of pollution, degradation of desalination's infrastructures, and high operating costs. We can conclude that regulatory compliance rate is one of the main issues discussed by DECSI framework
P30	Stakeholder Participation Levels	Moderate	As mentioned earlier, different agencies are involved in the desalination sector. However, research institutions and public reviews through open platforms have moderate integration in the desalination process.	Like P26, stakeholders have an effective role in planning, regulating, financing, operating, and managing desalination projects but without high levels of stresses on decision-making
P31	Transparency and Reporting Quality	Weak	Egypt lacks field investigations and quality reports available or national open-access database for most desalination plants. There are only a few data available from the Ministry of Housing or Holding Company for Water and Wastewater. Data about brine disposals, environmental negative effects, financial issues, and the operation of the desalination plants are rare and, if available, they are not updated and aggregated.	Transparency and Reporting Quality can help - Increase the confidence of the desalination process among public as well as PPP sector and their investments - Increase community engagement - Monitoring and evaluation of sustainability targets and our current performance in the desalination plants - International funding encouragement.

4. Results

The analysis of the DECSI framework and its application to Egypt is discussed showing the current performance rate of each parameter (weak–moderate–strong) and its importance. Tables 7–11 show the 31 indicators, comments on their current performance rates and importance from review and available data. For display clarity, indicator ratings are shown as categorical (Weak/Moderate Strong), but all computations use the underlying 1–5 scale defined in Section 2.2.

Qualitative ratings were converted into a five-point numerical scale (1 = weak, 3 = moderate, and 5 = strong), with intermediate bands as per usual protocol in composite indicator systems [13,27]. This allowed for the computation of average values for each of the five iWater dimensions and the composite index. Table 12 and Figure 4 show the average iWater Scores for Egypt's Desalination Sector and the five dimensions of DECSI.

Table 12. Average iWater scores for Egypt's desalination sector and the five dimensions of DECSI framework (D, E, C, S, I).

Dimension	Average Score (1–5)	Qualitative Interpretation
D	3.00	Moderate
E	3.00	Moderate
C	2.00	Weak–moderate
S	2.71	Weak–moderate
I	2.67	Weak–moderate

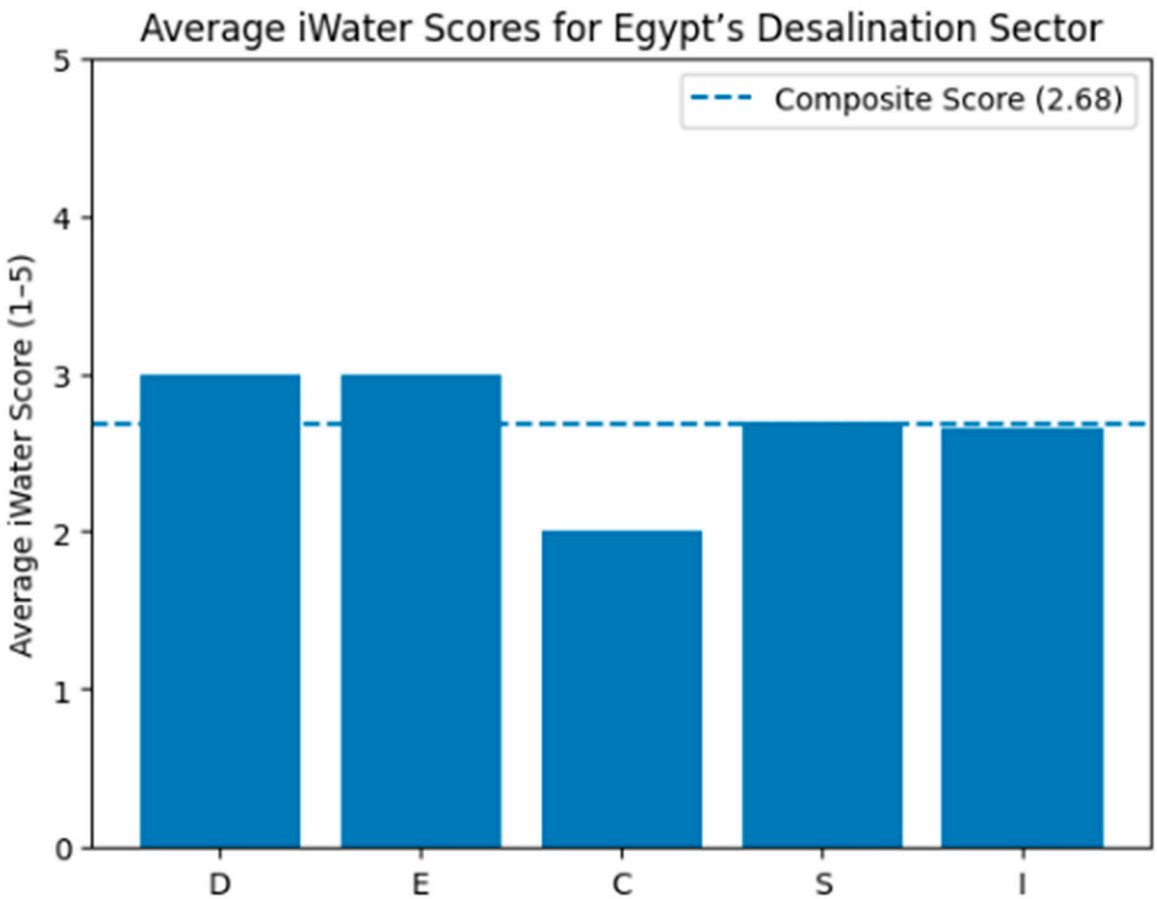

Figure 4. Average iWater scores for Egypt's desalination sector across the five DECSI dimensions.

The overall composite iWater Index score for the Egypt desalination sector is 2.68/5, which speaks of weak–moderate performance. Among the five dimensions, C-dimension (2.00) was the lowest, while D-dimension (both 3.0) registered medium performance. S-dimension (2.71) and I-dimension (2.67) also remained in the weak–moderate zone. These findings provide insight that in the future, climate-resilience approaches in desalination in Egypt should be emphasized in addition to other aspects.

5. Discussion

Based on the performance rating of 31 indicators for the five dimensions of iWater, Egypt's overall iWater Index is 2.68 on a scale of 5, or a weak–moderate performance level. The result reflects real progress in the expansion of desalinated water supply, in incorporating ecosystem considerations, and in strengthening institutional engagement. It also points to the need for significant improvement—particularly in climate change adaptation, disaster resilience, transparency, and inclusive development. Priorities going forward should therefore focus on constructing resilience while addressing equity and governance limitations toward stronger and more sustainable desalination-linked water security. This confirms that Egypt's desalination sector is positioned in a transition phase, progressing beyond early pilot phases but not yet achieving a strong and sustainable integration across all dimensions.

Dimension-wise, D- and E- dimensions showed better performance than the other dimensions. This shows that initiatives aimed at water quality improvement, plant reliability, and initiation points for environmental protection activities (e.g., compliance with brine discharge studies) are beginning to take effect. In contrast, the weakest dimension was C-dimension. The low scores on parameters of exposure to sea-level rise, incorporation of disaster risk reduction, and adaptive management capacity together emphasize the low resilience of Egyptian desalination infrastructure to long-term climatic stressors.

S-dimension also presented considerable challenges. While desalination provides a useful supplementary water supply in coastal areas, its benefit remains geographically uneven, and the cost of desalinated water constitutes potential barriers to more widespread affordability. This limitation is particularly evident for agriculture, as desalination is not economically scalable for Egypt's field-crop production due to its high cost and energy intensity, and should therefore be limited to targeted, high-value coastal farming and urban–industrial supply rather than replacing Nile-based irrigation.

Similarly, I-dimension only recorded moderate performance with particular weaknesses in terms of transparency and openness of data availability. Public reporting is minimal and there are fragmented institutional roles that restrict the sector from full adherence to sustainability and accountability expectations.

Most specifically, the governance issues of Egypt's desalination sector are the scattering of institutional functions across several ministries and organizations, the overlapping mandates that delay decision-making, and weak coordination mechanisms. Transparency and public disclosure remain partial, eroding public trust and private sector participation. Furthermore, stakeholder participation in planning and monitoring arrangements remains in its infancy, with resulting gaps in accountability and inclusiveness. Cumulatively, these obstacles limit the industry's ability to effectively integrate desalination into a coherent national water strategy.

Overall, the heatmap portrayal (Figure 5) makes it clear that Egypt's desalination sector is characterized by a dominance of medium-level performances, punctuated by occasional high performances and outright weak points. This is reflective of a system that has recorded measurable achievements in the scaling up of desalination capacity and meeting drinking water needs but continues to be faced with significant challenges in terms of climate resilience, socio-economic inclusivity, and governance transparency.

These findings stress that the route to Egypt's sustainable desalination requires not only continued technical development, but also stronger institutional coordination, environmental safeguards, and climate adaptation planning. However, a combination of desalination with other strategies for effective water resource management, like renewable energy technologies, water reuse practices, and demand management practices, may provide a significant positive effect on long-term water sustainability. But in long-term

strategies on desalination, there may arise challenges of energy dependence and sustainability. The DECSI model is therefore not only a diagnostic tool to uncover performance gaps, but also a roadmap for the identification of priority areas for future improvement along the five dimensions.

D-dimension		E-dimension		C-dimension		S-dimension		I-dimension	
Para	Per.	Para	Per.	Para	Per.	Para	Per.	Para	Per.
P1	Weak	P7	Moderate	P13	Strong	P19	Moderate	P26	Moderate
P2	Moderate	P8	Moderate	P14	Weak	P20	Moderate	P27	Moderate
P3	Strong	P9	Moderate	P15	Weak	P21	Weak	P28	Moderate
P4	Moderate	P10	Moderate	P16	Weak	P22	Moderate	P29	Moderate
P5	Moderate	P11	Moderate	P17	Weak	P23	Moderate	P30	Moderate
P6	Moderate	P12	Moderate	P18	Moderate	P24	Moderate	P31	Weak
						P25	Moderate		

Figure 5. Preliminary heatmap of the 31 DECSI parameters, showing current performance of each indicator (weak, moderate, strong).

The results from this study are specific to the Egyptian context. However, the DECSI-iWater framework inherently has the capability to be adapted for other countries and regions. Conventional modifications to indicator definitions, data sources, and weighting schemes allow application of the methodology in other institutional, environmental, and socio-economic contexts, which enables comparative assessment of desalination strategies at different scales.

This work is the first study to use the DECSI framework in Egypt, and the primary aim was therefore to establish evidence of the feasibility and potential for application of the methodology and not to deliver a definitive analysis of the Egyptian desalination industry. Presenting the study as a pilot application is aimed at highlighting that piloting and demonstrating the framework is the strength and future studies can build on this using more comprehensive datasets and field-based information. Future studies will focus on empirical validation of the DECSI framework through participatory scoring, expert elicitation, and benchmarking with established indices (e.g., World Bank's Water Security Index).

It should be emphasized that the DECSI approach is a flexible tool rather than a rigid measurement protocol. Not all indicators must be implemented simultaneously, as several of them may require dedicated, research-intensive studies. In this initial application, the assigned values for Egypt provide a first-order impression rather than definitive measurements. The purpose is to illustrate how the framework can be applied in practice and to stimulate further empirical studies. Future research can refine the assessment through field-based ecological data, household-level surveys, and advanced modeling, thereby enhancing the robustness of the index.

6. Conclusions

Desalination has become a strategic response to water scarcity in semi-arid and arid regions, particularly where rainfall is limited and groundwater resources are increasingly overutilized, and it now represents a crucial component of the Egyptian National Water Resources Plan. However, desalination is not merely a technical solution and must be addressed from multiple sustainability perspectives. In this context, this study presented the DECSI framework as a comprehensive approach for assessing desalination sustainability using 31 parameters across five dimensions: D, E, C, S, and I. The performance of each indicator in Egypt was evaluated using qualitative ratings (low, moderate, and strong), while highlighting their broader relevance within the national water security context.

The results indicate that Egypt demonstrates a relatively moderate performance across most dimensions of the desalination sector, particularly for dimensions D and E. In contrast, the C dimension exhibited the weakest performance, despite Egypt's high exposure to future climate-related risks. These findings underscore the need for enhanced integration of climate resilience and adaptive management considerations within desalination planning and infrastructure development. Quantitatively, the overall composite iWater Index score for the desalination sector in Egypt is 2.68/5, which reflects weak-to-moderate performance, and the dimension of Climate Resilience has the lowest score of 2.00/5.

Moreover, the analysis carried out in the study highlights the fact that, without appropriate integration with the current distribution networks, the frameworks of IWRM, and multi-source supply schemes, the contribution of desalination to water security is limited. This is due to high non-revenue water, the fragmentation of the sector, and poor adaptive governance, which impede the efficiency and effectiveness of desalination plants, especially in the coastal cities of Egypt due to the increased pressure from the burgeoning population and the tourism sector. This implies that the positioning of desalination should be within a national water security framework and not seen as an isolated solution.

The DECSI framework was designed as a flexible and adaptable tool intended for application across diverse geographical, economic, and institutional contexts. Although Egypt was used as a case study, the structure of the framework allows for the adaptation of indicator selection, weighting schemes, and data sources to suit local conditions, thereby supporting its transferability and applicability beyond the Egyptian context.

The significance of this research lies in demonstrating the practical applicability of a multi-faceted sustainability assessment approach, highlighting both areas of progress and critical gaps within the desalination sector. By positioning the study as an applied pilot, the findings illustrate the utility of the framework in supporting decision-making, improving subsequent data collection efforts, and informing more rigorous sustainability appraisals. As the framework continues to be refined, DECSI has the potential to serve as an influential tool not only for Egypt but also for other arid and desert regions facing increasing water scarcity. The framework also has diagnostic utility in that it aids in the prioritization of interventions, which, in turn, helps in determining where improvements would maximize benefits towards increased resilience.

Finally, these findings hold clear policymaking implications, particularly in linking desalination licensing and planning processes to sustainability standards, strengthening transparency mechanisms, and incorporating DECSI-based assessments into national strategies such as Egypt's Vision 2030. These results also reflect the importance of stakeholder engagement, infrastructure upgrade, and adaptive management, especially for coastal communities that are most exposed to system risk.

7. Limitations

Because up-to-date, comprehensive data on desalination across Egypt is still scarce, some current-status scores rely on rough estimates, or figures gathered from secondary sources. Readers should therefore treat the accompanying heatmap and commentary as a helpful first glance rather than an unalterable final word. Although the scores were cross-checked against established global and regional schemes, their order still carries a degree of personal judgment. Even so, documenting each parameter in full is vital; doing so reveals where information is missing, points future studies toward those gaps, and supplies policymakers with evidence they can actually use when steering desalination toward sustainable ends.

Key information such as brine discharges, environmental impacts, revenues, and plant performance is rarely reported or outdated. To mitigate these gaps, we cross-checked

government and academic sources and adopted a conservative scoring approach, though the absence of a national open-access database continues to limit robustness. Future studies should use rigorous field experiments, continuous monitoring of plant performance, and open reporting to strengthen the repeatability and consistency of the DECSI approach in Egypt.

Recommendations for Future Research and Policymaking

Given the present study is the initial application of the DECSI framework, several lines of future research and practical policy initiatives are intimated to improve desalination sustainability assessments. Future applications of DECSI could incorporate structured stakeholder workshops to co-produce scores and improve legitimacy.

Future Research Priorities:

- Comparative applications: Application of the DECSI framework to other countries across MENA for benchmarking desalination performance.
- Validation and benchmarking: Future applications should compare DECSI against international indices to enhance robustness and credibility.
- Scenario modelling: Simulate desalination performance over different development trajectories and policy scenarios.
- Sensitivity analyses: Test the sensitivity of the DECSI framework outcomes to variation in individual indicator scores (± 1) and changes in indicator weights will be tested to assess their influence on both dimension and composite indices.
- Climate integration: Integrate different climate change scenarios (high temperature, sea-level rise, extreme climate events) into desalination sustainability assessments.
- Dynamic analysis: Append time-series data to track performance change over time.
- Long-term monitoring: Establish systematic monitoring of the 31 DECSI indicators to capture sectoral progress and adaptation over time.

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