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Multi-criteria data-driven framework for drainage water reuse sustainability

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ABSTRACT

Agricultural drainage water reuse (ADWR) is a critical supplement to water resources amid escalating shortages. However, its sustainability faces complex challenges. This study developed a multi-criterion, data-driven framework incorporating key sustainability criteria such as water quality, water quantity, changes in freshwater salinity, monitoring network, and operational costs to assess ADWR practices. The framework was applied to Egypt's Eastern Nile Delta using water quality and quantity data from 2018 to 2023. Results identified Hanut reuse station as the most sustainable, while Saft ranked lowest due to its severe effect on freshwater salinity. ADWR increased steadily to 2.602 billion cubic meters annually, with an additional 1.879 billion cubic meters potentially achievable through sustainable mixing practices. Salinity significantly affects long-term reuse viability, emphasizing the need for adopting brackish water desalination. This study offers practical insights into ADWR sustainability, with recommendations to enhance the model's inclusiveness for sustainability assessments in arid regions and globally.

1. Introduction

Water scarcity represents one of the most pressing global challenges, particularly affecting nations in arid and semi-arid regions [1]. In Egypt, water scarcity is a significant challenge, given the limited and irregular supply of freshwater resources [2]. The country receives a fixed allocation of 55.5 billion cubic meters annually from the Nile River, representing its principal water source [3]. Rainfall is extremely limited, yielding less than 1.5 billion cubic meters annually, barely enough to support limited rain-fed agriculture [4].

Further complicating the situation, the accessible groundwater is non-renewable, with fossil aquifers potentially providing only 5.1 billion cubic meters per year. Accessing this groundwater demands significant infrastructure investment [5]. Egypt's heavy reliance on the Nile River, which accounts for nearly 97 % of the country's freshwater supply, highlights the magnitude of the water crisis in the country.

In this regard, the water balance indicates a large deficit, with annual water requirements surpassing available freshwater resources by approximately 20.5 billion cubic meters (MWRI 2017). Beyond these challenges, the Nile River Basin faces other challenges that add more pressure on scarce water resources and affect the long-term reliability of the water supply, including dam projects in the Upper Nile and climate change [6]. Considering these challenges, projections paint a concerning picture for the future, with the water deficit expected to escalate to 51 billion cubic meters per year by 2050 [7].

The agricultural sector consumes about 65 billion cubic meters annually, approximately 86 % of the total water needs [8]. This indicates that enhancing irrigation efficiency is the top priority in Egypt, as even a modest improvement in this aspect could potentially free up enough water to satisfy the entire industrial sector's needs. While improving irrigation efficiency can be a difficult and costly task, particularly when integrating advanced irrigation technologies and effective irrigation scheduling [9], other alternative approaches can achieve high levels of overall irrigation efficiency. Among these approaches is drainage water reuse (DWR), which has proven to be a highly promising alternative for improving the efficiency of water use in agriculture [10]. DWR pays back much faster and at much less cost than irrigation improvements, at least in the short term. Therefore, Egypt has made significant steps in this realm, widely practiced in the Nile Delta [11].

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Egypt initiated its drainage water reuse program for irrigation in the late 1970 s, employing direct application or blending with fresh water based on salinity levels. This policy is supported by an intensive monitoring network to track both water quantity and quality in the main drains and some irrigation canals of the Nile Delta and Fayoum. Nowadays, DWR is widely practiced through many practices, including official, unofficial, and intermediate reuse [3]. Official reuse is mainly practiced by mixing drainage water into irrigation canals through two different approaches [12]; either by gravity or pumping to irrigation canal. Additionally, there are 23 mixing PS constructed on the main drains in the Nile Delta, and an additional 9 mixing PS in the El Fayoum governorate.

Unlike official reuse, unofficial reuse is practiced by individual farmers who decide when and how to supplement their irrigation with drainage water [13]. Within the same context, an intermediate reuse policy was developed to address the associated risks of unofficial reuse and to undermine the pollution in the main drains that collect many sources of pollutants from urban areas [11,14].

DWR practices face multi-dimensional challenges in sustaining the current reuse level, particularly regarding uncertainness concerning drainage water quality and quantity. Some reuse pump stations, particularly in the Eastern Nile Delta, were interrupted for extended periods due to low-quality drainage water (DRI, 2005). However, DWR remains a crucial component of any future reclamation project driven by the escalating water shortage. This calls for a thorough assessment of current reuse practices at a regional level and determining the sustainability degree of each reuse practice. Further, explore opportunities for extra reusing drainage water [15].

DWR sustainability depends on several critical factors or critaria affecting the viability and effectiveness of the reuse process. Consistent and sufficient drainage water supply at the reuse pump stations is essential. The greater the availability of drainage water beyond current usage, the more likely the reuse process will be sustainable [15]. Drainage water quality is another major constraint on the reuse process. Higher compliance with relevant laws and standards enhances the sustainability of water reuse, both in the short and long term [16,17].

The impact of drainage water on freshwater salinity after mixing is a crucial factor in assessing sustainability. Increased salinity can adversely affect soil health and crop productivity. As Corwin [18] noted, sustainable water reuse in California's San Joaquin Valley relies on continuous monitoring, periodic leaching with fresh water, and effective subsurface drainage to prevent excessive salt accumulation. In contrast, terminating reuse or poor management can rapidly lead to the development of saline-sodic soils.

Furthermore, having an effective water quality and quantity monitoring network is essential for the sustainable reuse of agricultural drainage water. A Water Quality Monitoring Network (WQMN) is the primary tool for reliably collecting data on the physicochemical and bacteriological characteristics of drainage water [19].

Finally, operational cost plays a critical role in evaluating the sustainability of water reuse projects. Greater emphasis is often placed on direct reuse practices that avoid the need for treatment, desalination, or pumping stations, as these are the most cost-effective options. Conversely, practices involving treatment tend to incur significantly higher operational costs, which can diminish their economic sustainability [20].

The interrelated factors involved, each with different units and dimensions, necessitate a multi-criteria decision-making approach to effectively evaluate and prioritize drainage water reuse practices while accounting for their complex interactions. Methods such as EDAS (Evaluation based on Distance from Average Solution), Entropy Weighting, and the Fuzzy Analytic Hierarchy Process (FAHP) have been demonstrated as suitable techniques for this purpose [21].

The primary objectives of this research are to conduct a comprehensive assessment of current drainage water reuse (DWR) practices and to investigate the opportunities and challenges associated with expanding reuse in the Eastern Nile Delta. This region, characterized by a semi-arid climate and significant water scarcity, exemplifies the urgent need for sustainable water management strategies, including the reuse of agricultural drainage water. Additionally, the study aims to evaluate the sustainability of agricultural DWR and to develop a practical, data-driven framework that can assess and guide sustainable drainage water reuse within this arid environment.

2. Data-driven framework for drainage water reuse sustainability

This developed framework comprises five modules strategically structured for agricultural drainage water reuse managment; Module 1: Comprehensive Diagnostic Analysis, Module 2: Sustainability Factors Analysis, Module 3: Sustainability Analysis, Module 4: Regional Assessment for Drainage Water Reuse, and Module 4: Investigation of the Opportunities for extra quantity of drainage water reuse.

2.1. Module 1: comprehensive diagnostic analysis

Drainage water reuse for agricultural applications demands careful consideration of water quality, as its suitability for irrigation directly influences soil health and crop productivity. While identifying key water quality parameters (WQPs) is essential, prioritizing these parameters through a systematic weighting process is equally important. This prioritization is critical for conducting sustainability analyses and evaluating compliance in water reuse projects.

Beyond water quality, other sustainability criteria also require weighting. These include the adequacy of drainage water supply, the impact of drainage water on freshwater salinity after mixing, the presence of a reliable water quality and quantity monitoring network, and the operational costs associated with reuse projects.

To address these objectives, structured questionnaires were developed and distributed to an expert panel. This panel included specialists in water quality, agriculture, irrigation, and drainage from both Egypt and the international community. Such structured questionnaires are a key tool for gathering expert insights on these complex issues [22].

While formal multi-criteria decision-making methods like the Analytic Hierarchy Process (AHP) offer advantages such as structured pairwise comparisons and consistency checks, this study used direct averaging of expert ratings. This method was preferred for its practicality, efficiency, and its ability to incorporate diverse stakeholder perspectives. Additionally, it provides a transparent and straightforward approach that is well-suited to contexts requiring rapid consensus among experts located in different regions.

2.2. Module 2: sustainability factors analysis

This module primarily targets the sustainability criteria of agricultural drainage water reuse practices, and consequently, a sub-model has been developed for each sustainability criterion.

2.2.1. Monitoring network evaluation protocol

Water Quality Network is the exclusive tool that can reliably collect data on the physicochemical and bacteriological properties of drainage water [19]. This sub-model is designed to evaluate the adequacy of the monitoring network in tracking water reuse practices. The optimal monitoring of drainage water reuse requires a minimum of three monotring locations within each reuse scheme; drainage water, freshwater sources before mixing, and fresh water after mixing. This sub module employs a quantitative scoring system as: optimal monitoring (100 % score) when all three points are operational; partial monitoring (66 %) with two monotring locations; minimal monitoring (33 %) with only one point; and deficient monitoring (0 %) when no monitoring points exists.

The evaluation begins with a systematic review of existing monitoring network for both water quality and quantity parameters at each reuse locations. Subsequently, spatial and temporal gap analyses are performed to identify coverage deficiencies, forming the basis for targeted recommendations to enhance monitoring network robustness and data reliability.

2.2.2. Drainage water quantity analysis

This sub-model aims to identify a critical factor in the sustainability of Drainage Water Reuse projects, which is the adequacy of Drainage water. Within this model, the quantity of reused water and its percentage of the total available drainage quantity at the reuse pump station are calculated. Subsequently, the ratio of unreused drainage water to the reused quantity is determined. A higher ratio indicates stronger sustainability in reuse practices, while a lower ratio suggests the opposite. Analytical methods such as descriptive statistics and survival analysis are effective tools for achieving these objectives [23].

2.2.3. Water quality compliance assessment

This model aims to calculate the compliance percentage of each water quality parameter (WQPs) with regulations and standards specified for water reuse policies, whether local such as Egyptian Law No. 48 of 1982, Article 51, or global standards such as those established by the FAO. To accurately calculate the compliance percentage for each WQPs, Process Capability Analysis technique was employed.

This tool works by fitting a data distribution to calculate the actual area under the curve, bounded by the minimum and maximum specification limits. For each tested parameter, the compliance percentage with regulations is first determined. scince water quality parameters have varying relative importance, these compliance percentages are then normalized. Normalization is achieved by multiplying each parameter's compliance percentage by its relative weight and then averaging these weighted values across all parameters. This process yields a single compliance value that represents the overall conformity of water quality standards for each drainage water reuse practice. These values form a critical component of the decision matrix, which serves as the foundation for the subsequent sustainability analysis of water reuse policies.

2.2.4. Canal water salinity after-mixing

Salinity is a major challenge in drainage water reuse because it adversely affects soil salinity and crop productivity. Even tertiary treatment plants often fail to sufficiently reduce salinity levels. Therefore, salinity management is paramount when initiating any new water reuse practice. This sub-model evaluates the actual impact of drainage water reuse on freshwater resources by either directly measuring salinity before and after mixing at fully monitored stations or by calculating salinity after mixing using a salt load equation for partially monitored stations.

It is important to note that the percentage increase in salinity after mixing serves as an inverse indicator of sustainability, lower increases correspond to more sustainable practices. To maintain consistency within the decision matrix, where higher values represent greater sustainability, the model transforms this measure by subtracting the percentage increase from 100 %. This adjusted value directly reflects the sustainability ratio.

2.2.5. Drainage water reuse operational cost

This sub-model addresses a critical criterion for the sustainability of ADWR projects and practices, which is the operational cost of each project. Direct gravity-based reuse practices, which are widespread in Upper Egypt, can be considered the least costly and thus receive the highest classification with a score of 5 points. Meanwhile, practices that utilize only pumping stations without treatment are moderately costly and therefore receive a medium classification with a score of 3.5 points. While practices requiring treatment before mixing are high-cost and consequently receive a low classification with a score of 1.5 points.

2.3. Module 3: comprehensive sustainability analysis using EDAS methode

Following the analysis of sustainability criteria, it becomes essential to apply a multi-criteria analysis method to assess the degree of sustainability among elements that differ in dimensions and scoring [24]. One such technique is the EDAS (Evaluation based on Distance from Average Solution) method. Developed by Keshavarz Ghorabaee, Zavadskas, Olfat, and Turskis in 2015, EDAS is a sophisticated multi-criteria decision-making (MCDM) approach designed to evaluate sustainability performance across multiple dimensions simultaneously. This method offers an efficient framework by identifying optimal alternatives based on their distance from an average solution. It effectively distinguishes among options by quantifying both positive and negative deviations relative to this average, thereby enhancing the robustness of sustainability assessments.

EDAS procedure beginning with the construction of an initial decision matrix where alternatives are represented as columns and criteria as rows. Each element in this matrix represents how well a particular alternative performs against a specific criterion.

Once the matrix is established, the next step involves calculating the average solution for each criterion by taking the mean value across all alternatives. Eq. (21.2) is used to determine the average solution of each attribute.

$$\mathrm{Avi} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{m}} \mathrm{r}_{\mathrm{ij}}}{\mathrm{m}} Avi = \frac{\sum_{i=1}^{m} r_{ij}}{m} \mathrm{j} = 1, \cdots, \mathrm{n} \tag{2.1}$$

After determining the average solution, the method calculates two types of distances: positive distance from average (PDA) and negative distance from average (NDA). The PDA measures how much an alternative performs better than the average, while the NDA indicates how much an alternative performs worse than the average. These distances are calculated for each alternative against each criterion. PDA and NDA of the positive attributes are calculated by Eqs. (2.2) and (2.3), respectively.

$$PDA_{ij} = \frac{\max(0, (r_{ij} - AVj))}{AV\mathrm{j}} i = 1, \dots, m, j = 1, \dots, n \tag{2.2}$$

$$NDA\mathrm{ij} = \frac{\max(0, (AVj - r_{ij}))}{AV\mathrm{j}} i = 1, \dots, m, j = 1, \dots, n \tag{2.3}$$

Its crucial for these distances to be weighted according to the weight of the attributes or criterion, ensuring that the assessment reflects the relative significance of each parameter within the overall sustainability framework. Therfore, the process continues with the determination of weighted sums of these distances. This involves multiplying the PDA and NDA values by the respective criterion weights and then calculating the weighted sum for both positive and negative distances. Eqs. (2.4) and (2.5) used to determine the values of the weighted PDA and weighted NDA of each alternative, respectively.

$$SP_{i} = \sum_{j=1}^{m} PDA_{ij} {}^{*} W_{j} i = 1, \cdots, m \tag{2.4}$$

$$SN_{i} = \sum_{j=1}^{m} NDA_{ij} {}^{*} W_{j} i = 1, \cdots, m \tag{2.5}$$

This step involves normalizing the weighted sums and combining them to obtain a final score for each alternative. Normalization is essential because it converts these values to a common scale, typically between 0 and 1, which allows for fair comparison across alternatives. For the positive distance measure (PDA), normalization is performed by dividing each alternative's weighted sum by the maximum weighted sum among all alternatives. This creates what is called the Normalized Positive Distance (NPD) and Normalized negative Distance (NND) Eqs. (2.6) and (2.7) are used to normalize the values of the weighted PDA and weighted NDA, respectively.

$$NSP_i = \frac{SP_i}{\max(SP_i)} i = 1, \cdots, m \tag{2.6}$$

$$NSN_i = \frac{SN_i}{\max(SN_i)} i = 1, \cdots, m \tag{2.7}$$

After obtaining the normalized values for both positive and negative distances, the appraisal score (AS) calculated for each alternative by taking the average of these two normalized values as Eq. (2.8)

$$AS_i = \frac{NSP_i + NSNi}{2} i = 1, \cdots\cdots, m \tag{2.8}$$

This appraisal score represents a comprehensive evaluation of each alternative, considering both how much better it performs than the average (positive distance) and how much worse it performs than the average (negative distance). The appraisal score ranges from 0 to 1, with higher values indicating better alternatives. A higher appraisal score indicates a better alternative. Finally, the alternatives are ranked based on their appraisal scores, with the highest score representing the best alternative.

2.4. Module 4: regional assessment for drainage water reuse

This model aims to draw a comprehensive profile of agricultural drainage water reuse at the regional level by analyzing water quantity and salinity parameters while identifying general trends in reuse practices. This information is essential for long-term planning and decision-making regarding drainage water reuse projects. This begins first by calculating regional averages for quantity and Total Dissolved Solids (TDS) using the salt load equation. Descriptive analysis and data visualization techniques, including frequency histograms and whisker plots, are crucial tools for effectively determining spatial and temporal patterns and drawing a comprehensive profile of ADWR at the regional level.

The quality and quantity of water in drainage systems exhibit significant seasonal variations due to changes in weather patterns, hydrological conditions, and agricultural and human activities [25]. These fluctuations can introduce skewness in water quality and quantity measurements. To address this, seasonal decomposition techniques are employed, which break down time-series data into distinct components, separating long-term trends from cyclical seasonal variations [26]. By adjusting for seasonality, the analysis provides a clearer understanding of trends in drainage water quantity and total dissolved solids (TDS), revealing long-term patterns and supporting data-driven water resource management decisions [27]. A forecasting model is then developed using the seasonally adjusted data to predict future trends in drainage water volume and TDS levels.

2.5. Module 5: investigating opportunities of extra drainage reuse

This model aims to explore opportunities for expanding agricultural drainage water reuse in the study area through two strategic approaches; increasing water quantities in existing practices and projects, or implementing entirely new reuse practices. This assessment will be accomplished through comprehensive statistical analysis of water quantity and quality parameters, with particular emphasis on evaluating compliance ratios for water quality standards in un-reused drains. This also includes determining the appropriate type of reuse practice for each potential expansion opportunity and identifying the necessary corrective measures required before implementing the practice. The methodology systematically evaluates drainage water characteristics to recommend optimal reuse applications (direct irrigation, blending with freshwater, or specific crop selection) based on water quality profiles. Fig. 1 shows the Data-driven framework for drainage water reuse sustainability.

3. Case study; eastern nile delta

3.1. Drainage catchements in the Eastern Nile Delta

In the Eastern Nile Delta, located within a semi-arid climate zone, there are five drainage catchments as shown in Fig. 2: Farskour and El-Serw, El-Mataria, Bahr Hadous, Bahr El-Baqar, and El-Mahsama (Drainage Task Force Committee, 1997). In the north-western part of the Eastern Nile Delta region, Farskour drain collects a mixture of municipal and agricultural drainage water. In this catchment, DWR practices are carried out through Farskour PS, which diverts a portion of the Farskour drainage water into El-Salam Canal. However, a considerable quantity of drainage water in this catchment still discharges into Lake Manzala.

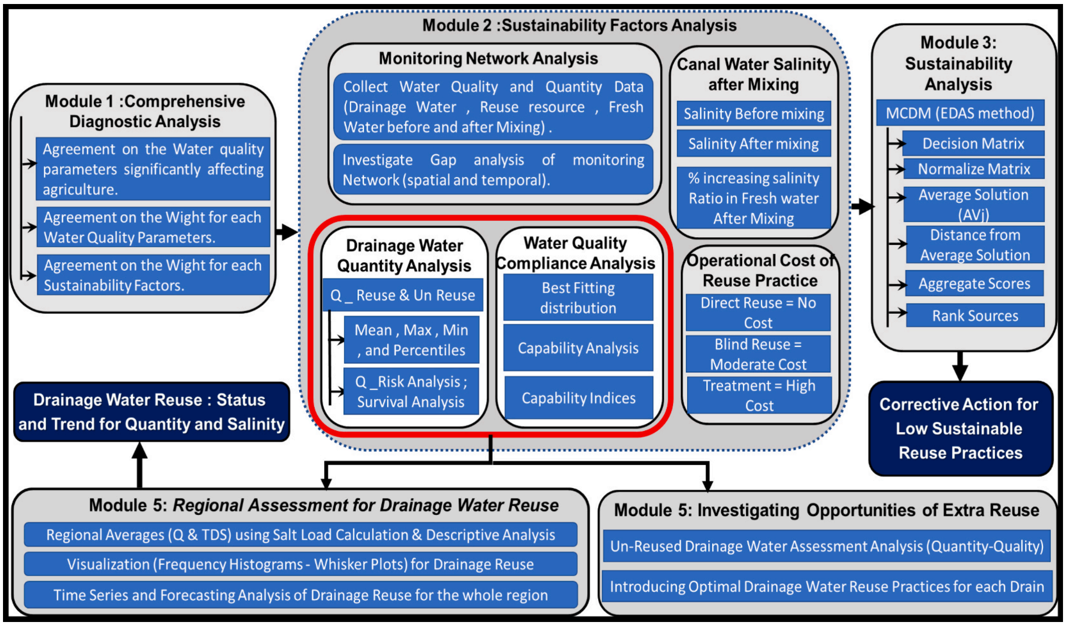

Fig. 1. Data-driven framework for drainage water reuse sustainability.

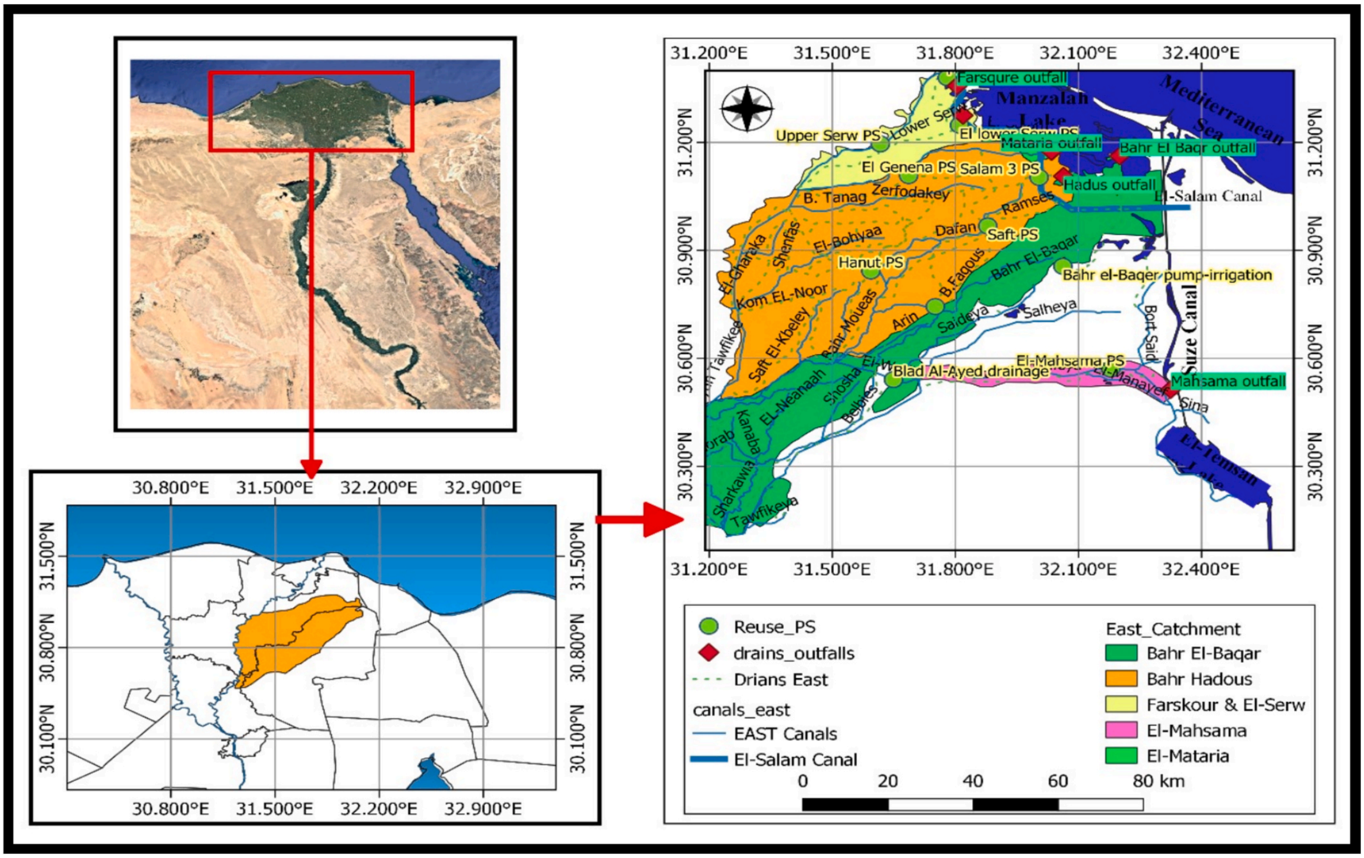

Fig. 2. Drainage Catchments and Official DWR PS in Eastern Nile Delta.

Downstream from the Farskour catchment and slightly eastward lies El- Serw catchment, which contains the Upper Serw, Lower Serw, and El-Atway drains. In this catchment, DWR practices are carried out via the Lower Serw PS which diverts part of the Lower Serw drainage water into El-Salam Canal, while a considerable quantity of drainage water from this catchment flows into Lake Manzala.

In the North of the Eastern Nile Delta region, there is the El-Mataria catchment, which includes El-Tawel, El-Ahmadiea, and El-Mataria drains. However, there is no reuse practice in this catchment, and all drainage water flows directly into Lake Manzala.

Hadous drainage, the largest catchment in this region, is located in the middle and extends from west to north. Within this catchment, several DWR practices are carried out via Hanut PS, Saft PS, and El–Genena PS, while a significant quantity from Bahr Hadous drain is reused in El-Salam Canal via El-Salam PS No.3. Despite this, some drainage water of this catchment still flows directly into Lake Manzala.

In the Eastern fringes of the Eastern Nile Delta region, Bahr El-Baqar drainage catchment collects both excess irrigation water and the treated/ partially treated sewage water from a long strip extending from East Cairo to Lake Manzala. Within this drainage catchment, DWR is practiced through the Blade El-Ayed PS and Bahr El-Baqar PS. Meanwhile, the new Bahr Al-Baqar treatment plant aims to withdraw and treat large quantities from the drains of Bahr Al-Baqar, Shadr Azzam, and Om El-Rish.

Within El-Mahsama drainage catchment, drainage water from El-Mahsama drain is lifted by the El-Mahsama pump station and passes under the Suez Canal to reach the El-Mahsama Treatment Plant. The treated water is then mixed with Sinai Canal, while the remaining untreated drainage water keeps flowing into El-Temsah Lake [28].

3.2. Data sources and collection methods

This study utilized water quality and quantity data from the National Water Quality Monitoring Network (NWQMN), operated by the Drainage Research Institute (DRI) under Egypt's Ministry of Water Resources and Irrigation. The NWQMN comprises 174 sites, with standardized protocols for data collection and analysis. Monthly field measurements and laboratory analyses were conducted for key water quality parameters, including salinity indicators. Flow data in open locations were measured using Acoustic Doppler Current Profilers (ADCP), while pump station quantities were calculated from operational records maintained by the Mechanical and Electrical Authority. Data from 31 monitoring sites across the Eastern Nile Delta were selected based on spatial and temporal representation. The dataset covers the period from August 2018 to July 2023. A summary of data sources, methods, and coverage is presented in Table 1.

Importantly, it should be noted that the water quality and quantity data presented in this study already reflect the cumulative influence of climate-driven changes (e.g., shifts in water salinity, temperature, and availability), even if these drivers are not explicitly separated in this analysis. While we fully recognize their centrality to understanding regional water management challenges, the scope of our study, which focused on water quality and quantity monitoring, and data limitations, does not permit a direct, quantitative integration of climate change as a sustainability criterion.

4. Results and discussions

4.1. Module 1: comprehensive diagnostic analysis

A structured expert-based approach was adopted to (1) identify the most influential water quality parameters (WQPs) affecting soil and

Table 1
The summary of data sources and collection methods.

Pameter/data	Data source	Collection method	Responsible institute	Period covered	No. of locations
TDS, DO	NWQMN	Field measurements	DRI	Aug 2018 – Jul 2023	31
Other WQPs	NWQMN	Lab analysis	DRI/NWRC	Aug 2018 – Jul 2023	31
Water quantity in open locations	NWQMN	ADCP device measurement	DRI	Aug 2018 – Jul 2023	19
Water quantity of Pump Stations	NWQMN	Calculated from operational records	DRI/Mechanical & Electrical Authority	Aug 2018 – Jul 2023	12

plant health in irrigation, (2) determine their relative weights, and (3) establish the sustainability criteria and corresponding weights for drainage water reuse projects. This methodology was selected to integrate both theoretical expertise and practical field experience, thereby enhancing the robustness and applicability of the framework to real-world conditions.

4.1.1. Expert elicitation and questionnaire design

A targeted questionnaire was distributed to twenty specialists in water quality, irrigation, drainage, water resources, agriculture, and environmental science, both within Egypt and internationally. The expert panel comprised professionals with extensive experience in their respective domains, ensuring a comprehensive and informed assessment of the relevant parameters and criteria.

4.1.2. Identification and weighting of water quality parameters

A structured expert judgment approach was employed to determine the relative weights of Water Quality Parameters (WQPs) impacting soil and plant health. The expert panel was asked to rate the importance of each WQP using a Likert-type scale. Individual ratings for each parameter were then aggregated across all respondents, and the resulting averages were normalized by dividing by the sum of all criterion averages.

Analysis of the survey responses revealed 13 key WQPs with significant influence on soil and plant health under irrigation as summarized in Table 2. The Sodium Adsorption Ratio (SAR) and Total Dissolved Solids (TDS) were rated as the most critical factors, receiving normalized weights of 0.18 and 0.17, respectively, reflecting their central role in irrigation water quality management. By contrast, Total Suspended Solids (TSS) had the lowest relative weight (0.02), indicating its minimal impact in the context of this study.

The identification of Sodium Adsorption Ratio (SAR) and Total Dissolved Solids (TDS) as the most influential water quality parameters in this study aligns with findings from international research, where [29,30,31] demonstrated that these indices are among the most negatively affecting soil and crop productivity. While elevated SAR values in irrigation water can impair soil structure and permeability, high TDS levels can induce osmotic stress, both leading to significant reductions in crop yield and quality. These findings provide valuable insights for decision-making in water reuse initiatives, particularly in Egypt and similar regions.

4.1.3. Determination of sustainability criteria weights

Following the same methodology applied in weighting water quality parameters, the relative importance of sustainability criteria water quality, salinity impact, drainage water availability, Water Quality Monitoring Network (WQMN), and operational costs was determined through a structured expert rating process. Each criterion was rated by the panelists using a Likert scale (1–5), and individual ratings were averaged across all respondents. To ensure the weights were suitable for multi-criteria analysis, each average was normalized by dividing by the sum of all criterion averages, yielding a set of weights that sum to 1.0.

Table 2
Water quality parameters significantly affecting soil and plant health in irrigation.

Parameter	Weight	Parameter	Weight
SAR (Sodium Adsorption Ratio)	0.18	COD (Chemical Oxygen Demand)	0.06
TDS (Total Dissolved Solids)	0.17	DO (Disolved Oxygen)	0.05
NO3 (Nitrate)	0.10	Boron	0.05
pH	0.08	TN (Total Nitrogin)	0.04
Cl (Chloride)	0.08	Fe (Iron)	0.03
BOD (Biological Oxygen Demand)	0.08	TSS (Total Suspended Solids)	0.02
TP (Total Phosphorus)	0.06	Total	1.00

The analysis of the responces rveled that for instance, water quality received the highest average rating (4.2 out of 5), resulting in a normalized weight of 0.35. Salinity impact and drainage water availability each received average ratings of 2.4, corresponding to weights of 0.20. The remaining criteria were assigned proportionally lower weights based on their average ratings (WQMN and operational costs each at 0.125). This weighting scheme directly reflects the collective judgment of the expert panel, with water quality consistently prioritized as the foremost factor influencing the sustainability of water reuse projects in the study region.

These conclusions are supported regional case studies in Egypt [32,30], which consistently identify water quality as the primary constraint for sustainable agricultural water reuse in arid and semi-arid environments.

4.2. Module 2: sustainability factors analysis

4.2.1. Monitoring network analysis

The results presented in Table 3 revealed significant heterogeneity in monitoring coverage. For example, the Faraskour Mixing Plant demonstrated exemplary coverage, with monitoring conducted above and below the mixing point along the Salam Canal, earning a 100 % score. In contrast, the Bahr El Baqar irrigation water mixing station was monitored at only a single point (drainage water), reflecting partial coverage (33 %) and a critical gap in assessing the environmental impact downstream. These gaps are primarily attributable to constraints in financial and human resources, compounded by the high recurring costs of field sampling, laboratory analysis, and logistics, particularly in remote or extensive water reuse sites.

To improve the effectiveness and sustainability of water quality monitoring, it is advisable to adopt cost-effective, technology-driven solutions such as Internet of Things (IoT) sensors and online monitoring stations. These innovations enable real-time, automated data collection, significantly reducing reliance on labor-intensive and costly manual field sampling and laboratory analyses. However, the deployment of such technologies must address operational and security challenges, particularly the risk of theft and vandalism at remote sites. Mitigation strategies may include the use of tamper-proof station designs, proactive engagement with local communities, and partnerships with municipal authorities to enhance site security.

While remote sensing and drone-based technologies offer the potential for broader spatial coverage and could further strengthen monitoring networks, their applicability in the Egyptian context may be constrained by the narrow width of many irrigation and drainage waterways, which limits the effective deployment of such platforms.

Given these practical and financial constraints, implementing smart monitoring protocols represents a pragmatic approach. For example, transitioning to a rotational monitoring schedule increasing the total number of monitored sites while reducing the sampling frequency at each location (e.g., from monthly to bimonthly) can provide more

Table 3
Results of the water quality monitoring review in reuse projects.

PS	Monitoring points Drainage water	Canal befor mixing	Canal after mixing	Total monitoring points	Monitoring score
Frasqur	√	√	√	3	100
Lower Serw	√	√	√	3	100
El-Salam No.3	√	√	√	3	100
El-Genena	√	√	×	2	66
Blad El-Ayed	√	√	√	3	100
B. El-Baqar Irrigation	√	×	×	1	33
Hanut	√	√	√	3	100
Saft	√	×	√	2	66
El-Mahsama WTP	√	√	×	2	66
El-Salam New WTP	√	√	√	3	100

comprehensive spatial coverage and improve the representativeness of the data, without substantially increasing costs.

4.2.2. Drainage water reuse assessment analysis

Descriptive and survival analysis were conducted for each DWR pump station and the findings revealed that, **Frasqur PS** pumps approximately 23.7 million cubic meters monthly from the Frasqur drain into El-Salam Canal with an average acceptable salinity of around 701 ppm. However, this quantity represents only 52 % of the drainage water at frasqur drain. This means that there is another un-reused quantity, estimated by 93 % of the reused quantity, which provides powerful indicators for sustainability and opportunities for expansion in reuse quantity from this source. The same analysis was applied to the other nine reuse stations, revealing significant variation in the ratio of unreused to reused water (a key drainage quantity sustainability indicator). While this ratio reached 100 % at Bahr El-Baqar Irrigation, Hanut, Saft, El-Mahsama WTP, and El-Salam New WTP, it was notably lower at other stations: 86 % (El-Salam No. 3), 70 % (Blad El-Ayed), 30 % (Lower Serw), and 25 % (El-Genena).

These results demonstrate a considerable potential to increase drainage water reuse from stations like Frasqur, El-Salam No. 3, Bahr El-Baqar Irrigation, Hanut, Saft, El-Mahsama WTP, and El-Salam New WTP, where the ratio of unreused to reused water approaches or reaches 100 %. However, opportunities for expansion are more limited at stations such as Blad El-Ayed, Lower Serw, and El-Genena. Table 4 represents the detailed results of the drainage water quantity assessment analysis.

4.2.3. Water quality compliance analysis

A comprehensive water quality compliance analysis was conducted for ten mixing reuse stations in the study area. The assessment was based on standards specified in Article 51 of Egyptian Law No. 48 of 1982, and FAO criteria for parameters not covered by Egyptian legislation. Since each water quality parameter carries a different relative weight in terms of its impact on soil and plant health, the data were normalized by multiplying the compliance percentage of each parameter by its predetermined relative weight to calculate a weighted score. The overall compliance rate for each station was then determined by summing the weighted scores across all 13 selected water quality parameters.

Table 4
The results of the drainage water quantity assessment analysis.

PS	Total Quantity in the drain (M m^3/month)	% Reused of the total Quantity	% Un-Reused of the total Quantity	% Un-Reused from the Reused Quantity
Frasqur	45.60	52	48	93
Lower Serw	67.59	77	23	30
El-Salam No.3	133.30	54	46	86
El-Genena	9.40	80	20	25
Blad El-Ayed	6.62	58	42	70
B. El-Baqar Irrigation	8.06	50	50	100
Hanut	3.04	47	53	150 = 100
Saft	22.96	30	70	233 = 100
El-Mahsama WTP	56.0	50	50	100
El-Salam New WTP	264.0	6.43	93.56	1455 = 100

The compliance analysis results indicated that a station like Faraskour demonstrated complete compliance (100 %) with standards for most tested WQPs. However, exceptions were noted for DO, TN, and TSS, which showed compliance rates of 21 %, 98 %, and 95 %, respectively. Since each WQP has a different relative weight, the data were normalized through a weighted calculation process. This was accomplished by multiplying each parameter's compliance percentage by its corresponding relative weight to generate individual parameter scores. The overall compliance rate was then determined by aggregating these weighted scores across all 13 selected water quality parameters, yielding a unified compliance value of 95.9 %.

The same analysis was applied to the other nine reuse stations, and as shown in Table 5, the weighted compliance value ranged from a high of 97.20 % at El-Mahsama WTP to a notably lower score of 80.0 % at El-Baqar WWTP. The relatively low compliance at El-Baqar WWTP highlights the importance of carefully considering elevated levels of Total Dissolved Solids (TDS) and Sodium Adsorption Ratio (SAR) observed at this station.

Given these findings, addressing these water quality challenges through targeted mitigation measures is essential to improve compliance and ensure the sustainability of water reuse practices. This nuanced and comprehensive weighted compliance analysis underscores its value in guiding informed water resource management decisions that consider differential impacts of key water quality parameters on agricultural and environmental outcomes.

4.2.4. Canal water salinity after mixing

Average salinity measurements before and after mixing were analyzed for reuse stations under complete water quality monitoring. The mean percentage increase in salinity due to mixing was calculated for these stations. For partially monitored stations, post-mixing salinity levels were estimated using the salt load equation. The analysis revealed varying degrees of salinity elevation after mixing. In stations such as El-Geneina and Hanout, the increase was marginal at 5 %. For example, in the El-Bahr El-Sagier canal, salinity increased from 266 to 278 ppm after mixing with El-Geneina reuse p.s, indicating high sustainability potential for these reuse practices. Conversely, mixing drainage water from Saft El-Qebli drain into El-Defan Canal had a segnificunt effect, with salinity raising from 275 to 1450 ppm, a 427 % increase. Given these findings it is imperative to prioritize targeted mitigation strategies—such as advanced desalination and salinity management at stations facing critical salinity challenges to enhance overall drainage water reuse sustainability.

Since the percentage increase in salinity serves as an inverse

Table 5
The results of Weighted Compliance Analysis (WCA) for official DWR in the Eastern Nile Delta.

WQPs	*WQ Standards*	*Wight*	*Hanut P. S*		*Saft P. S*		Genena *P. S*		*Blad El-Ayed P. S*		*Bahr El-Baqar P. S*	
			%	*Score*	*%*	*Score*	*%*	*Score*	*%*	*Score*	*%*	*Score*
SAR	0–6	0.18	82	14.8	78	14.0	89	16.0	93	16.7	83	14.9
TDS	0–2000	0.17	100	17.0	91	15.5	100	17.0	100	17	100	17.0
pH	6.5–8.5	0.08	78	6.2	98	7.8	89	7.1	100	8	100	8.0
NO3	0–20	0.10	90	9.0	100	10.0	100	10.0	100	10	100	10.0
CL	0–70	0.08	100	8.0	100	8.0	100	8.0	100	8	100	8.0
BOD	0–30	0.08	83	6.6	78	6.2	80	6.4	75	6	78	6.2
COD	0–30	0.06	78	4.7	89	5.3	82	4.9	91	5.4	45	2.7
TP	0–3	0.06	100	6.0	100	6.0	100	6.0	100	6	100	6.0
TN	0–15	0.04	88	3.5	61	2.4	82	3.3	78	3.1	68	2.7
DO	> 5	0.05	0	0.0	15	0.8	4	0.2	0	0	0	0.0
Boron	0–0.7	0.05	100	5.0	100	5.0	100	5.0	100	5	100	5.0
TSS	0–50	0.02	95	1.9	89	1.8	88	1.8	93	1.8	78	1.6
Fe	0–3.0	0.03	100	3.0	100	3.0	100	3.0	100	3	100	3.0
Final Score		**85.70**	**85.90**	**88.70**	**90.20**	**85.20**						
WQPs	*WQ Standards*	*Wight*	*Farskour P. S*		*Serw P. S*		*El-Salam P. S No.3*		El-Mahsama WTP		El-Salam WWTP	
			%	*Score*	*%*	*Score*	*%*	*Score*	*%*	*Score*	*%*	*Score*
SAR	0–6	0.18	100	18.0	98	17.6	92	16.6	100	18.0	85	15.3
TDS	0–2000	0.17	100	17.0	100	17.0	98	16.7	88	15.0	0	13.0
pH	6.5–8.5	0.08	100	8.0	98	7.8	93	7.4	100	8.0	100	8.0
NO3	0–20	0.10	100	10.0	100	10.0	100	10.0	100	10.0	100	10.0
CL	0–70	0.08	100	8.0	100	8.0	100	8.0	100	8.0	100	8.0
BOD	0–30	0.08	100	8.0	100	8.0	93	7.4	100	8.0	100	8.0
COD	0–30	0.06	100	6.0	100	6.0	93	5.6	100	6.0	100	6.0
TP	0–3	0.06	100	6.0	100	6.0	100	6.0	100	6.0	100	6.0
TN	0–15	0.04	98	3.9	93	3.7	88	3.5	100	4.0	100	4.0
DO	> 5	0.05	21	1.1	4	0.2	16	0.8	85	4.3	93	4.7
Boron	0–0.7	0.05	100	5.0	100	5.0	100	5.0	100	5.0	100	5.0
TSS	0–50	0.02	95	1.9	92	1.8	89	1.8	100	2.0	100	2.0
Fe	0–3.0	0.03	100	3.0	100	3.0	100	3.0	100	3.0	100	3.0
Final Score		**95.9**	**94.20**	**91.80**	**97.20**	**80.0**						

sustainability indicator as lower increases indicates higher sustainability, a transformation was necessary for decision matrix compatibility. Conventionally, lower values in decision matrices indicate less sustainable practices. Thus, the applied transformation was: Sustainability Indicator = 100 % – (% Salinity Increase). This adjustment produced effective indicators suitable for sustainability assessments. Table 6 presents the final transformed indicators for post-mixing salinity increases.

4.2.5. *Operational cost of reuse practices*

A comprehensive review was conducted to evaluate the operational practices of ten water reuse stations within the study area, focusing on their cost efficiency. The assessment examined the technological approaches and processes employed at each station, with particular attention to treatment methods and mixing operations. To quantify operational costs, a scoring system was developed, where higher scores reflected greater cost-effectiveness.

The findings showed that most reuse stations primarily rely on mixing practices using pumping stations, placing them in the moderate-cost category with an average cost-efficiency score of 3.50. In contrast, El-Mahsama WTP and El-Salam WTP utilize more resource-intensive processes involving treatment followed by mixing. Due to this added complexity, these stations incur higher operational costs and received lower cost-efficiency scores of 1.50.

These results indicate that mixing and intermediate reuse practices tend to be more economical than full treatment processes, provided the water quality is suitable for reuse without extensive treatment.

4.3. *Module 3: sustainability analysis*

The decision matrix was developed based on the sustainability factor analysis results obtained from Model 2. This matrix organizes individual drainage water reuse practices as coulmns and established sustainability criteria (including water supply availability, quality compliance, salinity impact, monitoring network effectiveness, and DWR operational cost) as columns. It integrates the calculated values for each sustainability criterion across all ten water reuse stations within the study area. Each

Table 6
Salinity increasing ratio and final transformed indicators for post-mixing salinity.

PS	TDS (mg/l) of Reused Water	TDS (mg/l) of Canal Befor Mixing	TDS (mg/l) of Canal After Mixing	Salinity Increasing ratio	100 % − Increasing ratio
Frasqur	701	269	290	8	92
Lower Serw	760	290	401	38	62
El-Salam No.3	1269	418	865	106	−6
El-Genena	570	266	278	5	95
Blad El-Ayed	568	256	390	52	48
B. El-Baqar Irrig.	916	258	498	72	28
Hanut	868	256	270	5	95
Saft	1575	275	1450	427	−327
El-Mahsama WTP	1307	320	905	183	−83
El-Baqar WWTP	2219	870	1130	30	70

criterion is presented alongside its corresponding relative weight, as shown in Table 7, facilitating both individual assessments and a holistic sustainability analysis.

The average solution (AVj) was computed across all criteria using Eq. (2.1), and results presented in Table 8.

Next, the positive (PDA) and negative (NDA) distances from the average for each reuse station were determind using Eqs. (2.2), (2.3) for positive atributes. These distances are reported in Table 9.

Table 10: The negative distances from the average for each reuse pump stations.

Using Eqs. (2.4), (2.5), we then calculated the weighted PDA and NDA values (denoted as SPi and SNi) for all reuse stations, and the results presented in Tables 10.

Subsequently, the weighted positive distance from average (SPi) and negative distance from average (SNi) were normalized to obtain NSPi and NSNi (Table 11) via Eqs. (2.6) and (2.7). Finally, the appraisal score (ASi) was calculated for each station using Eq. (2.8), determining their sustainability rankings.

The results obtained from the sustainability analysis approach show that Hanut reuse station, with highest appraisal score, is the most promising and sustainable among other reuse stations. Frasqur (0.8951) and El-Genena are ranked as 2nd and 3rd top sustainable, respectively. However, Saft reuse pump station is ranked as the worst alternative among the reuse stations by getting lowest appraisal score. This significant difference underscores serious sustainability challenges at Saft station, mainly driven by the extreme impact of drainage water reuse on freshwater salinity, which has severely limited its sustainability prospects. Similarly, this issue also affects the sustainability potential of the Mahsama station, emphasizing the need for improved strategies to mitigate salinity levels and enhance long-term viability.

Given Hanut station's high sustainability ranking and Saft station's low ranking primarily due to elevated salinity impacts, it is imperative to prioritize targeted mitigation strategies—such as advanced desalination and salinity management at stations facing critical salinity challenges to enhance overall drainage water reuse sustainability.

Although Bahr El-Baqar treatment plant has demonstrated a reasonable level of sustainability, this is largely attributed to its relatively low operational capacity compared to the freshwater inflow at El-Sheikh Jaber Canal. However, once the station reaches full capacity, its sustainability may be compromised due to the resultant increase in water salinity in El-Sheikh Jaber Canal after mixing, mirroring challenges observed at Saft station. Elevated salinity levels pose potential adverse effects on downstream ecosystems, including degradation of soil quality, reduced agricultural crop yields, and harm to aquatic biodiversity. These environmental impacts underscore the need for proactive salinity management and mitigation strategies to safeguard both agricultural productivity and ecological health in the canal's downstream areas.

The similar international systems like California's San Joaquin Valley demonstrates that large-scale agricultural drainage water reuse faces significant salinity and monitoring challenges, yet remains achievable through proper management including continuous monitoring, salt-tolerant crops, and adaptive policies 33,34. India's Indira Gandhi Canal, has successfully transformed arid landscapes but faces ongoing challenges with waterlogging and secondary salinization that require management strategies including efficient water application, drainage infrastructure, and participatory farmer engagement [35]. [36] experts recommend integrating traditional and scientific knowledge into collaborative policies to address soil salinity and waterlogging issues for sustainable development.

Table 8
Average solution (AVj) for drainage water reuse practices.

Reuse P. S	DW availability	DW quality	100 % − increasing	Existing WQMN	Cost of practice
Frasqur	93	95.9	92	100	3.5
Lower serw	30	94.2	62	100	3.5
El-Salam No.3	86	91.8	10	100	3.5
El-Genena	25	88.7	95	66	3.5
Blad El-Ayed	70	90.2	48	100	3.5
B. El-Baqar Irr.	100	85.2	28	33	3.5
Hanut	100	85.7	95	100	3.5
Saft	100	85.9	−327	66	3.5
El-Mahsama WTP	100	97.2	−83	66	1.5
El-Baqar WWTP	100	80	70	100	1.5
AVj	80.4	89.48	9.00	83.1	3.1

In Summary, there are a universal necessity for integrated monitoring systems, comprehensive salinity management strategies, and adaptive policy frameworks to achieve sustainable water reuse on a global scale [37], thereby promoting resilience and long-term environmental and socio-economic benefits worldwide.

4.4. *Drainage water reuse regional assessment*

4.4.1. *Basic statistics analysis*

To quantify and evaluate water reuse practices at the regional scale of the Eastern Nile Delta, Monthly average water reuse quantities were first computed for ten central mixing stations, which represent official water reuse in the region from August 2018 to July 2023. Then the monthly average salt load for all reused water was calculated using the salt load equation. This analysis produced a new dataset of monthly averages for both water quantities and salt loads, reflecting the total reused drainage water in the Eastern Nile Delta.

Descriptive statistical analysis was conducted on the computed dataset, revealing that the average quantity of reused drainage water in the Eastern Delta was approximately 216.86 Mm^3 per month (2.602 billion cubic meters annually) with acceptable average salt load of about 931 ppm. The 95th percentile value for reused drainage water was 314

Table 7
Decision matrix for drainage water reuse sustainability analysis.

Reuse P. S	DW availability	DW qualitycompilance rate	100 % − increasing rate in salinity	Existing WQMN	Cost of practice
Weight	**0.20**	**0.35**	**0.20**	**0.125**	**0.125**
Frasqur	93	95.9	92	100	3.5
Lower Serw	30	94.2	62	100	3.5
El-Salam No.3	86	91.8	−6	100	3.5
El-Genena	25	88.7	95	66	3.5
Blad El-Ayed	70	90.2	48	100	3.5
B. El-Baqar Irr.	100	85.2	28	33	3.5
Hanut	100	85.7	95	100	3.5
Saft	100	85.9	−327	66	3.5
El-Mahsama WTP	100	97.2	−83	66	1.5
El-Baqar WWTP	100	80.0	70	100	1.5

Table 9
The positive and negative distances from the average for each reuse pump stations.

Reuse P. S	DW availability		DW quality		100% − increasing		Existing WQMN		Cost of practice	
	PDA	NDA	PDA	NDA	PDA	NDA	PDA	NDA	PDA	NDA
Frasqur	0.157	0.0000	0.072	0.0000	9.222	0.0000	0.203	0.0000	0.129	0.0000
Lower Serw	0.000	0.6269	0.053	0.0000	5.889	0.0000	0.203	0.0000	0.129	0.0000
El-Salam No.3	0.070	0.0000	0.026	0.0000	0.111	0.0000	0.203	0.0000	0.129	0.0000
El-Genena	0.000	0.6891	0.000	0.0087	9.556	0.0000	0.000	0.2058	0.129	0.0000
Blad El-Ayed	0.000	0.1294	0.008	0.0000	4.333	0.0000	0.203	0.0000	0.129	0.0000
B. El-Baqar Irr.	0.244	0.0000	0.000	0.0478	2.111	0.0000	0.000	0.6029	0.129	0.0000
Hanut	0.244	0.0000	0.000	0.0422	9.556	0.0000	0.203	0.0000	0.129	0.0000
Saft	0.244	0.0000	0.000	0.0400	0.000	37.3333	0.000	0.2058	0.129	0.0000
El-Mahsama WTP	0.244	0.0000	0.086	0.0000	0.000	10.2222	0.000	0.2058	0.000	0.5161
El-Baqar WWTP	0.244	0.0000	0.000	0.1059	6.778	0.0000	0.203	0.0000	0.000	0.5161

Table 10
The weighted PDA and NDA for each reuse pump stations.

Reuse P. S	DW Availability		DW Quality		100 % − Increasing		Existing WQMN		Cost of Practice		SPi	SNi
	WPDA	WNDA	WPDA	WNDA	WPDA	WNDA	WPDA	WNDA	WPDA	WNDA		
Frasqur	0.031	0.000	0.072	0.000	9.222	0.0000	0.203	0.0000	0.129	0.000	1.942	0.000
El. Serw	0.000	0.125	0.053	0.000	5.889	0.0000	0.203	0.0000	0.129	0.000	1.238	0.125
El-Salam No.3	0.014	0.000	0.026	0.000	0.111	0.0000	0.203	0.0000	0.129	0.000	0.087	0.000
El-Genena	0.000	0.137	0.000	0.008	9.556	0.0000	0.000	0.2058	0.129	0.000	1.927	0.166
El-Ayed	0.000	0.025	0.008	0.000	4.333	0.0000	0.203	0.0000	0.129	0.000	0.911	0.025
El-Baqar Irr.	0.049	0.000	0.000	0.047	2.111	0.0000	0.000	0.6029	0.129	0.000	0.487	0.092
Hanut	0.049	0.000	0.000	0.042	9.556	0.0000	0.203	0.0000	0.129	0.000	2.001	0.014
Saft	0.049	0.000	0.000	0.040	0.000	37.333	0.000	0.2058	0.129	0.000	0.065	7.506
El-Mahsama	0.049	0.0000	0.086	0.0000	0.000	10.2222	0.000	0.2058	0.000	0.516	0.079	2.1347
El-Baqar WTP	0.049	0.0000	0.000	0.1059	6.778	0.0000	0.203	0.0000	0.000	0.516	1.430	0.1016

Table 11
Total sustainability score for DWR pump stations in Eastern Delta.

	SPi	SNi	NSPi	NSNi	ASi	**Rank**
Frasqur	1.942449696	0	0.790296695	1	0.8951	**2**
Lower Serw	1.237790216	0.125373134	0.503601981	0.986188679	0.7449	**5**
El-Salam No.3	0.086777436	0	0.035305893	1	0.5177	**7**
El-Genena	1.927240143	0.166583928	0.784108602	0.981648827	0.8829	**3**
Blad El-Ayed	0.91103315	0.025870647	0.370659013	0.997150045	0.6839	**6**
B. El-Baqar Irr.	0.487107473	0.092102182	0.198182443	0.989853865	0.5940	**8**
Hanut	2.001417542	0.014785427	0.814288097	0.998371212	0.9063	**1**
Saft	0.064885251	7.506391818	0.026398933	0.173082927	0.0997	**10**
El-Mahsama WTP	0.078952911	2.134682595	0.03212244	0.764839682	0.3985	**9**
El-Baqar WWTP	1.429732954	0.101597041	0.581694975	0.988807895	0.7853	**4**

Mm^3 per month, indicating that 95 % of reused quantities fall below this threshold. Additionally, 95 % of reused quantities have salinities below 1189 mg/l, which is well below the maximum limit of total dissolved salts (TDS less than 2000 mg/l) recommended by FAO standards for irrigation and outlined in Article 51 of Law 48 regulating drainage water reuse.

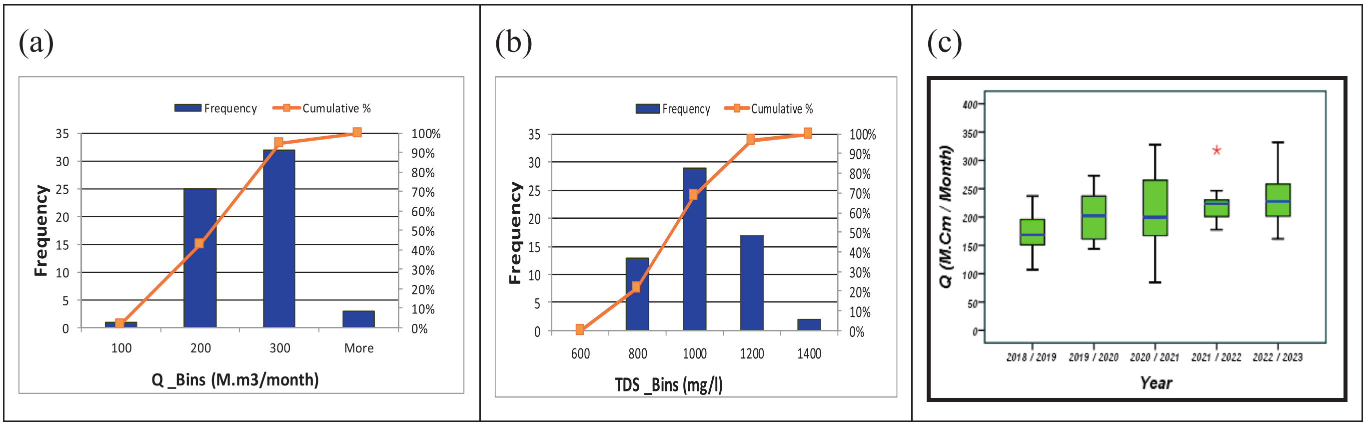

Fig. 3. (a) Frequency diagram for drainage water reuse in the Eastern Nile Delta. (b) Frequency diagram for TDS of drainage water reuse in the Eastern Nile Delta. (c) Whisker Plots for DWR in the Eastern Nile Delta.

The frequency histogram and Whisker Plots for total DWR (Mm^3/month) and Total Dissolved Salts (ppm) in reused water are illustrated in Fig. 3. The results indicated that the category ranging from 200 to 300 (Mm3/month) is the most frequent values in this distribution. Regarding the TDS values presented in Fig. 3(b), the most likely measurements fall between 800 and 1000 ppm. The Whisker Plot in Fig. 3(c) reveals that the annual median values fluctuated within a narrow range except for 2020–2021 as the measurements fluctuated within a relatively wider range. Over the five years from August 2018 to July 2023, the annual median of DWR increased from 173 to 216 Mm^3/month, signifying a nearly 25 % increase in DWR quantities.

4.4.2. *Seasonal decomposition and trend analysis*

Seasonal decomposition analysis was performed on total drainage water reuse (DWR) quantities from August 2018 to July 2023 to eliminate periodic fluctuations and seasonal variations from the time series data. The seasonal decomposition revealed a cyclical fluctuating pattern in the original data, with peaks and troughs occurring approximately annually, indicating the presence of seasonal variations. The seasonal component exhibited a repeating pattern each year, reflecting seasonality in water measurements. The analysis decomposed the original data into three components: the seasonally adjusted series, the smoothed trend cycle series, and the residual irregular fluctuations, as shown in (Fig. 4a).

The seasonally adjusted series removed regular seasonal fluctuations, providing a clearer representation of the long-term trend by minimizing the influence of irregular variations. This allowed for a more straightforward interpretation of the overall pattern. The smoothed trend cycle series revealed the underlying trend and cycle after eliminating both seasonal effects and random fluctuations, presenting a clearer long-term trend. Time series analysis of drainage water reuse (DWR) discharges in the Eastern Nile Delta indicated a statistically significant upward trend. The linear regression model for the seasonally adjusted data ($y = 1.392x + 168.61$), shown in (Fig. 4b), has a positive slope of 1.392, corresponding to an average increase of approximately 1.392 MCM per month each time period.

DWR discharges increased from about 160 MCM per month in August 2018 to approximately 255 MCM per month by July 2023, representing a total increase of around 59 %. This corresponds to an average annual increase of roughly 12 %. Moreover, year-to-year comparisons reveal consistent growth, with increments ranging between 10 % to 14 % annually over the study period. This quantitative evidence confirms a a statistically significant upward trend, reflecting ongoing improvements in drainage water reuse practices, likely driven by enhanced water management strategies in the Eastern Nile Delta.

4.5. *Opportunities of promoting drainage water reuse*

Unused agricultural drainage water in the eastern Nile Delta primarily flows into Lake Manzala via five main agricultural drains: Bahr El-Baqar, Bahr Hadous, El-Serw, El-Mataria, and Farskour, accounting for 98 % of the total inflow. This water reaches the lake either through pumping stations or by gravity. The El-Mahsama drain, however, discharges into Lake Timsah.

An assessment of the principal drains feeding into Lake Manzala and Lake Timsah shows that four of the six key drains; Farskour, El-Serw, Hadous, and El-Mahsama already engage in partial water reuse through sustainable practices, according to Model 3. This indicates significant potential to expand reuse efforts, possibly recovering an additional annual volume of approximately 262.7, 186.5, 735.8, and 336 million cubic meters from Farskour, El-Serw, Hadous, and El-Mahsama drains, respectively. The combined total of this potential reuse is around 1.52 billion cubic meters per year.

Conversely, the El-Matariya pumping station extracts roughly 708 million cubic meters annually from the Al-Hmadia and Al-Tawel El-Bahri drains, with an average salinity of 1,255 ppm. Despite meeting most regulatory requirements, except for dissolved oxygen, this water is not currently reused. Given its relatively high compliance with the salinity and water quality parameters set by Article 51 of Law 48, blending this water with fresh sources could represent an effective reuse strategy.

The Bahr El-Baqar drain contributes a substantial quantity of drainage water—an estimated 3.168 billion cubic meters per year to Lake Manzala but with a higher average salinity of about 2,119 mg/l and poor compliance with other water quality parameters, posing major challenges for direct reuse without advanced treatment. To address these issues, a new treatment plant for Bahr El-Baqar has recently been commissioned and is in trial operation, aiming to treat and reuse approximately 2 billion cubic meters annually. This will reduce the volume flowing untreated into Lake Manzala to less than 1.15 billion cubic meters. However, salinity remains a significant hurdle, as current treatment methods have yet to sufficiently lower salinity levels.

Overall, there are clear opportunities for increased reuse of drainage water in the Eastern Nile Delta through blending, direct irrigation, treatment, and desalination, depending on the specific characteristics and quality of each drain's discharge. The opportunities for reusing additional drainage water in the Eastern Nile Delta are presented in Table 12.

5. Summary and conclusion

Agricultural drainage water reuse (ADWR) is a main supplement to the water resources, driven by the escalating water shortage. However,

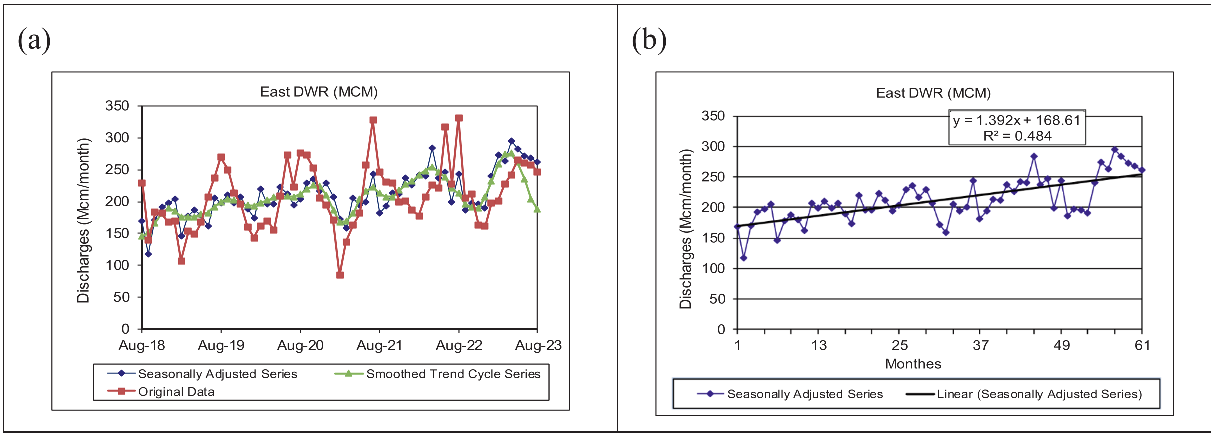

Fig. 4. (a) Timeseries decomposition for the DWR discharges in the Eastern Nile Delta. (b) Trend component for the drainage water reuse in the Nile Delta.

Table 12
The opportunities for reusing additional drainage water in the Eastern Nile Delta.

Drain	Discharge (million m^3/year)	TDS (mg/l)	% Law.48 article 51	Proposed practices	Proposed canal	Corrective action
El-Mataria	708.0	1154	82 %	Mixing	El-Salam Canal &El-Bahr El-Sagher	DO
El-Serw	186.50	741	84 %	Mixing &Direct Reuse	El-Salam Canal &Direct Irrigation	DO
Farskour	262.70	760	87 %	Mixing &Direct Reuse	El-Salam Canal &Direct Irrigation	DO
Bahr Hadous	735.80	1438	85 %	Mixing	El-Salam Canal	DO
El-Mahsama	336.0	1307		Treatment	El-shike Zayed Canal	Treatment
Bahr El-Baqar	3234.74	2119	24 %	Desalination	El-Salam Canal	Desalination

it faces considerable sustainability challenges, shaped by a web of interconnected factors and criteria. These include the availability and quality of drainage water, its influence on freshwater salinity, the need for a monitoring network, and the operational costs associated with its use. However, due to the intricate and interdependent nature of these sustainability criteria, no standardized or tested framework exists for assessing their long-term viability and investigating the opportunities for implementing new practices. This research aims to develop a data-driven framework for assessing drainage water reuse practices while ensuring their long-term sustainability.

This framework is strategically designed to manage agricultural drainage water reuse through five interconnected modules. **The first module**, Comprehensive Diagnostic Analysis, aims to identify key water quality parameters affecting agriculture, assess their significance for sustainability, and establish a systematic weighting of criteria for drainage water reuse projects. **The second module**, Sustainability Factors Analysis, focuses on analyzing and quantifying sustainability indicators across different drainage water reuse practices.

The third module, Sustainability Analysis, calculates the sustainability degree of each reuse practice using multi-criteria analysis techniques. **The fourth module**, Regional Assessment for Drainage Water Reuse, provides a comprehensive evaluation of the current state of agricultural drainage water reuse. Finally, **the fifth module**, Investigating Opportunities for Extra Drainage Water Reuse, aims to explore the potential for increasing the reuse of drainage water in agriculture and enhancing its long-term sustainability.

The developed framework was applied to the Eastern Nile Delta region in Egypt, encompassing ten drainage water reuse stations. The assessment utilized five years of historical data (August 2018 to July 2023), including water quantity measurements and thirteen water quality parameters selected by water quality experts: SAR, TDS, NO3, pH, CL, TP, TN, BOD, COD, DO, Boron, TSS, and Fe.

The results indicating that current monitoring of agricultural drainage water reuse in Egypt faces challenges due to financial and human resource limitations and the high costs of manual sampling, especially at remote sites. To improve sustainability, the adoption of cost-effective technologies like IoT sensors and online real-time monitoring is recommended. While remote sensing and drones can provide wider coverage, their use is limited by the narrow waterways in the region. Implementing rotational monitoring schedules that balance reduced sampling frequency with increased site coverage offers a practical and cost-efficient solution tailored to local constraints.

Regarding water quality and operational costs, compliance scores across reuse stations varied from 80 % to 97 %, with lower scores linked to elevated salinity indicators such as TDS and SAR. Mixing-based water reuse approaches showed moderate cost-effectiveness, whereas treatment-intensive processes were costlier and less efficient concerning mitigating salinity. These findings highlight the importance of focusing on advanced desalination and salinity control methods at critical stations to ensure sustainable reuse practices.

The sustainability analysis of drainage water reuse in Egypt's Eastern Delta identifies Hanut reuse station as the top performer, achieving the highest appraisal score and demonstrating strong potential for long-term viability. Frasqur (0.8951) and El-Genena stations rank second and third, respectively, reflecting well-managed reuse practices. In contrast, Saft reuse pump station emerges as the least sustainable, primarily due to the severe impact of drainage water reuse on freshwater salinity. This disparity underscores the critical influence of water quality particularly salinity on the success of water reuse initiatives.

The sustainability challenges at Saft, Mahsama, and Bahr El-Baqar stations are largely driven by increased salinity resulting from intensive drainage water reuse. As Egypt transitions toward higher levels of water reuse, proactive measures to mitigate salinity impacts on both water and soil are essential. Desalination of moderately saline drainage water emerges as a promising strategy to sustain agricultural productivity while safeguarding environmental health.

The full-capacity operation of the Bahr El-Baqar treatment plant is expected to exacerbate salinity levels in the El-Sheikh Jaber canal, potentially diminishing the station's long-term sustainability. Therefore, developing a comprehensive operational and management model for the plant, coupled with exploring innovative salinity reduction technologies, is imperative. Such strategies will be vital for optimizing the plant's performance and ensuring the sustainable reuse of Egypt's limited water resources.

Time series analysis of drainage water reuse reveals a statistically significant upward trend in quantity. Monthly discharges increased from approximately 160 million cubic meters (MCM) in August 2018 to about 255 MCM by July 2023, marking a total rise of nearly 59 %. This equates to an average annual growth rate of around 12 %. Year-to-year comparisons further confirm consistent increases, with annual growth rates varying between 10 % and 14 %. This positive trend reflects ongoing enhancements in water management and reuse strategies across the Eastern Nile Delta.

Further analysis indicates an annual potential to reuse approximately 1.879 billion cubic meters of drainage water for irrigation through mixing from the main drains: Farskour, El-Serw, El-Mataria, El-Mahsama, and Bahr Hadous. Even once the Bahr El-Baqar treatment plant reaches its full operating capacity of 2.0 billion cubic meters per year, around 1.152 billion cubic meters of drainage water will continue to be discharged annually into Lake Manzala. Effectively managing this residual flow, especially considering its elevated salinity, will necessitate innovative technological solutions, such as brackish water desalination, to expand safe reuse opportunities.

Egypt's experience reflects challenges common worldwide in salinity management and sustainable water reuse. While successes at Hanut and Farskour demonstrate effective approaches, difficulties remain at Saft and Bahr El-Baqar. These cases underscore the critical need for robust salinity control measures, integrated monitoring systems, and adaptive policies on a global scale.

This study presents a comprehensive, data-driven framework to evaluate the sustainability of agricultural drainage water reuse in water-scarce regions. It provides a decision-support tool for policymakers to identify suitable reuse sites, determine necessary corrective actions and interventions, and optimize resource allocation. By balancing water quality, quantity, and operational costs, the framework enables targeted measures such as pilot desalination projects. Its adaptive design supports the continuous integration of monitoring data, thereby enhancing policy development and management strategies over time.

Nonetheless, the framework has limitations, including data scarcity in developing regions and the exclusion of political, socio-economic, and transboundary factors that influence water reuse. Future research should adopt multidisciplinary approaches incorporating climate change impacts, governance structures, and social acceptance. Implementing targeted pilot studies on advanced desalination technologies, coupled with active stakeholder engagement, is recommended to improve the technical, economic, and social feasibility of water reuse—providing benefits for arid regions globally.

CRediT authorship contribution statement

M.M. Ibrahim: Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Mohamed Shaban:** Writing – review & editing, Validation, Conceptualization, Supervision, Methodology, Formal analysis. **Ehab Abd El-Karim:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abeer Samy:** Writing – review & editing, Validation, Conceptualization, Software, Supervision, Methodology, Formal analysis.

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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