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ORIGINAL ARTICLE

A multi-model approach for optimizing drainage water reuse sustainability in arid and semi-arid regions: a case study of El-Salam Canal project in Egypt

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Abstract

Sustainable drainage water reuse (DWR) in agriculture requires integrated assessment of water quality, soil dynamics, leaching requirements, and crop productivity. This study developed a novel multi-model framework integrating expert knowledge, multi-criteria decision analysis, hydraulic modeling (HEC-RAS), and soil–water-atmosphere-plant simulation (SWAP) to optimize operational strategies for Egypt's El-Salam Canal project. Three water supply reliability scenarios were evaluated: planned baseline, 95% reliability, and 75% reliability with seasonal variability. Model validation demonstrated robust performance (HEC-RAS: NSE = 0.88–0.94; SWAP: $R^2 = 0.89$, RMSE = 0.23 dS/m). The 75% reliability scenario achieved transformative improvements, including a 188.4% increase in integrated water quality score, a 25.5% reduction in Sodium Adsorption Ratio (from 7.15 to 5.33), and a 33.5% decline in Total Dissolved Solids (from 1706 to 1134 mg/L). Seasonal optimization, prioritizing high-quality drainage sources (El-Serw, Farskor, Hadous, El-Matria) during critical summer cropping periods, outperformed uniform year-round allocation. The planned scenario resulted in critical root zone salinity (ECe: 7.17 dS/m), causing predicted yield losses of 8.3% (wheat) and 38.9% (maize), while requiring intensive leaching (15.5% of irrigation). The 75% reliability—summer-oriented scenario reduced soil salinity by 49.1% to 3.65 dS/m ($P < 0.001$), maintained yields within 5% of optimal, and decreased leaching to 8.5%, saving 610 m^3/feddan/year. This framework provides actionable decision support for sustainable drainage water management in water-scarce regions, directly advancing SDGs 2 (Zero Hunger) and 6 (Clean Water and Sanitation) by maintaining crop yields, conserving water, and enhancing climate resilience through reduced soil salinity and freshwater dependence while preserving soil health.

Keywords Sustainable water management · Soil salinity · Water supply reliability · Leaching requirements · Drainage water reuse · Water quality · HEC-RAS model · SWAP model · Water-scarce regions

Introduction

The growing scarcity of freshwater has heightened the importance of drainage water reuse (DWR) as a cost-effective strategy and critical component of the water balance, particularly in arid and semi-arid regions (Helal et al. 2021). Egypt, the semi-arid country, exemplifies this approach through pioneering large-scale agricultural drainage water reuse initiatives, notably in the Nile Delta (Barnes 2014), including El-Salam Canal, El-Mahsama, and Bahr El-Baqr Water Treatment Plants (Raslan et al. 2020).

Despite these pioneering large-scale initiatives, the expansion and long-term viability of drainage water reuse remain constrained by critical environmental and

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operational barriers. This promising supplement faces several environmental and sustainability challenges, including soil degradation, groundwater contamination, and crop productivity decline (Ashour et al. 2021), (Yin et al. 2025). Pollutant loadings, originating from domestic and industrial sources, compromise drainage water quality, especially in developing regions with limited sewerage infrastructure, significantly constraining reuse success (Helmecke et al. 2020).

Among these multifaceted challenges is the negative effect of drainage water quality on soil–plant systems. The adverse impact of poorly regulated drainage water reuse policies on soil health is well-documented in the scientific literature. Among these effects, salinity remains a primary constraint to the sustainable reuse of drainage water (Machado & Serralheiro, (2017). Irrigation with saline drainage water progressively increases the accumulation of soluble salts and sodium ions within the root zone, thereby intensifying soil salinization, degrading soil structure and permeability, reducing long-term fertility, and raising the risk of ion toxicity in plants, which ultimately diminishes crop productivity (Yin et al. 2025). Mitigating salt accumulation caused by drainage water reuse requires extensive freshwater leaching to flush salts beyond the root zone; however, this high freshwater demand may compromise the intended water savings of reuse programs, particularly in water-scarce and saline environments (Okuda et al. 2020).

Compounding the salinity challenge, additional water quality parameters introduce further constraints on sustainable reuse. Beyond salinity, the presence of elevated sodium, chloride, and boron concentrations in irrigation water poses significant threats to agricultural productivity through the induction of osmotic stress and ion-specific toxicity, which collectively impair nutrient uptake and restrict plant growth (Łuczak et al. 2021). Elevated Sodium Adsorption Ratio (SAR) values are of particular concern, as excess sodium displaces calcium and magnesium from soil exchange sites, promoting clay dispersion and aggregate breakdown. This deterioration in soil structure results in reduced hydraulic conductivity, restricted aeration, and subsequently impaired root development and water accessibility (Nabayi et al. 2020). Compounding these chemical and structural challenges, the accumulation of total suspended solids (TSS) in irrigation water can progressively clog soil pores, thereby creating anaerobic micro-environments that inhibit root respiration and suppress the activity of beneficial aerobic soil microorganisms essential for nutrient cycling (Cheng et al. 2024).

These soil-level degradation processes are further exacerbated by vertical transport of contaminants. Additional concerns arise from the potential infiltration of salts and contaminants into both shallow and deep aquifer systems, particularly in regions characterized by inadequate drainage infrastructure or highly permeable soil profiles, thereby posing substantial risks to environmental integrity and public health (Sanad et al. 2024).

These multifaceted challenges have precipitated significant delays or complete suspension of large-scale water reuse projects globally (Mateo-Sagasta et al. 2023). In the Nile Delta region of Egypt, for instance, seven major reuse facilities have undergone temporary or permanent closure due to deteriorating water quality and salinization levels exceeding agronomically sustainable thresholds (El Gamal et al. 2005). Similarly, in Australia's recycled wastewater irrigation districts, progressive salt accumulation in soil profiles and underlying aquifers has compelled regulatory authorities to reassess the viability of expanding existing reuse schemes (Radcliffe & Page 2020). Analogous constraints have been documented across MENA countries, where government-supported reuse initiatives have been curtailed or discontinued following soil and groundwater salinity monitoring programs that indicated environmentally unsustainable conditions (Mateo-Sagasta et al. 2023). These documented cases of constrained or suspended DWR schemes across diverse geographical contexts, from Egypt's Nile Delta to Australia's irrigation districts and MENA countries, collectively demonstrate that technically feasible reuse initiatives often become environmentally unsustainable without robust assessment frameworks.

In response to these sustainability challenges, DWR assessment methodologies have progressively evolved over recent decades. Early methodologies relied predominantly on single-parameter indices such as electrical conductivity (EC) and sodium adsorption ratio (SAR) to establish irrigation water quality thresholds (Dudley & State 2008). While providing foundational guidance, these isolated indicators proved inadequate in capturing the multivariate impacts inherent in DWR systems. Subsequent developments introduced multi-criteria decision-making (MCDM) frameworks, including AHP, TOPSIS, and PROMETHEE, enabling systematic evaluation across water quality, economic, and environmental dimensions (Hajkowicz & Collins 2007). More recently, data-driven approaches have gained prominence in drainage water reuse management (Ibrahim et al. 2025).

(Lawal et al. 2023) developed multi-criteria data-driven models and coupled hydrologic-machine learning frameworks that leverage extensive monitoring datasets to predict reuse suitability and optimize management interventions. Additionally, statistical quality control frameworks have also been validated to ensure ongoing operational safety and sustainability through adaptive monitoring protocols and corrective action mechanisms (Helal et al. 2021). Survival analysis has been also applied to provide probabilistic evaluations of water resource availability (Christodoulou 2011) as a critaria of water reuse sustainability, with subsequent studies demonstrating its utility in supporting adaptive water management under uncertainty (Karamouz & Mohammadpour 2017) and (Shah et al. 2024). The Delphi technique has been employed to systematically synthesize expert opinions, addressing inherent uncertainties and guiding adaptive management strategies (López-gunn et al. 2024).

Despite these methodological advances, current DWR assessment frameworks remain fragmented. A systematic review of the previous studies reveals that no existing framework sequentially couples' experts' insights, multi-criteria assessment of drainage water sources, setting optimal operational strategies, scenarios—hydrodynamic simulation, water quality assessment, and soil salinity modeling within a unified architecture. For example, (Butcher & Wool 2021) applied HEC-RAS to optimize blending ratios in agricultural canals but did not integrate soil–water modeling to predict downstream salinization, leading to unforeseen soil degradation within two irrigation seasons. Conversely, (Ibrahim et al. 2025) employed MCDM frameworks for source selection but lacked mechanistic simulation of resulting water quality dynamics and soil salt accumulation. Similarly, (Gichamo et al. 2020) developed machine learning models for reuse suitability prediction but assumed static water availability, ignoring seasonal hydrological variability quantified through survival analysis.

This methodological isolation produces four critical deficiencies: (1) operational strategies are formulated without systematic integration of expert knowledge through weighted multi-criteria analysis, resulting in management decisions that prioritize short-term water availability over long-term sustainability indicators such as water quality and soil health preservation, leaching efficiency, (2) hydrodynamic models optimize blending without soil constraint feedback and without linking to long-term leaching requirements, (3) expert-based decision-making lacks probabilistic quantification of seasonal supply variability, and (4) water quality indices take the same weight neglecting the dieffrent effect for every parameter. Moreover, operational protocols developed without systematic expert elicitation (e.g., Delphi-based consensus) and weighted priority assessment failed to incorporate critical sustainability criteria resulting in operationally efficient yet environmentally unsustainable strategies (Ferrans et al. 2022), (Wang et al. 2019).

Consequently, existing frameworks cannot answer the integrated question: "What blending strategy simultaneously satisfies water availability constraints, regulatory compliance, hydraulic capacity, and soil salinity thresholds across multiple seasons while incorporating expert-validated sustainability priorities? This research gap necessitates a staged-integration multi-model framework that synergistically combines expert knowledge, comprehensive water quality assessment, regulatory compliance verification, seasonal variability analysis, uncertainty quantification, weighted multi-criteria evaluation, and advanced hydrological, water quality, and soil modeling tools (HEC-RAS and SWAP). Such a framework is essential for formulating sustainable operational strategies that preserve soil health and minimize leaching requirements while maintaining agricultural productivity (Wurtsbaugh et al. 2019), (Mishra et al. 2023).

Accordingly, this study is the first to consolidate these components into a unified staged-integration framework, thereby overcoming the fragmentation of prior approaches and enabling truly sustainable drainage water reuse strategies. The staged-integration framework combines expert elicitation through the Delphi technique, probabilistic water availability analysis using survival analysis, multi-criteria source evaluation, hydrodynamic simulation with HEC-RAS, and soil–water-crop modeling with SWAP. Unlike existing parallel-coupling approaches that require subjective reconciliation of conflicting model outputs, this framework enforces hierarchical constraint propagation wherein outputs from each analytical stage systematically inform and constrain subsequent modeling phases.

This sequential architecture embodies two fundamental advantages. First, the framework establishes physical constraint cascading, whereby water availability limits derived from survival analysis directly constrain permissible blending ratios in multi-criteria evaluation, which subsequently bound hydraulic simulations, thereby ensuring that downstream soil salinity predictions reflect realistic operational scenarios. Second, the methodology employs progressive scenario filtering, systematically eliminating operationally infeasible or environmentally unsustainable alternatives at each analytical stage before propagating them to subsequent models. This adaptive filtering prevents the generation of recommendations that violate unmodeled constraints, a persistent deficiency in parallel-integration frameworks where final outputs may be hydraulically feasible yet agronomically unsustainable.

Applied to Egypt's El-Salam Canal, a representative large-scale drainage water reuse system in arid environments, this framework demonstrates practical utility in formulating blending strategies that simultaneously satisfy seasonal water availability, regulatory water quality standards, canal hydraulic capacity, and long-term soil health preservation. The methodology provides a replicable template for optimizing drainage water reuse operations in water-scarce regions globally, delivering quantitative evidence that sustainability-focused water allocation enhances efficiency and productivity while conserving freshwater resources. The study directly advances Sustainable Development Goals related to food security and water sanitation by sustaining agricultural yields, improving irrigation water quality, and enhancing system resilience through reduced soil salinity and preserved long-term soil health.

Multi-model approach for optimizing drainage water reuse sustainability

The proposed framework operates through sequential data flow wherein outputs from each module constrain subsequent analytical stages (Fig. 1). This hierarchical coupling systematically propagates physical, statistical, and expert-derived constraints, eliminating infeasible scenarios progressively rather than requiring post-hoc reconciliation. Data collection (Module 1) and policy contextualization (Module 2) establish baseline conditions, while concurrent expert elicitation (Modules 3–4) generates normalized parameter weights. Module 5 implements a validation gateway, only datasets passing statistical stability criteria advance to reliability analysis; anomalous data trigger iterative refinement. Validated time series enter survival analysis (Module 6), producing sustainability thresholds that physically limit extraction rates, while capability analysis (Module 7) computes compliance scores weighted by expert priorities.

Module 8 consolidates quantity and quality constraints into a unified classification matrix, enabling Module 9 to formulate operational strategies. Strategies undergo coupled simulation: HEC-RAS (Module 10) generates water quality profiles serving as inputs to SWAP (Module 11) for soil impact assessment. Scenarios producing excessive salinization trigger refinement through Module 9; acceptable scenarios advance to comparative synthesis (Module 12). The architecture enforces three constraint levels: physical (Module 8) ensures only validated, probabilistically sustainable quantities proceed; and prevents reliance on non-compliant sources; agronomic (Modules 12) rejects hydraulically feasible yet environmentally unsustainable strategies. This progressive filtering distinguishes the framework from parallel-coupling approaches requiring subjective conflict resolution, ensuring all recommendations satisfy nested feasibility constraints.

Module 1: comprehensive survey and data collection

Comprehensive, high-quality data collection forms the cornerstone of the multi-model framework developed for optimizing drainage water reuse sustainability (Ibrahim et al.

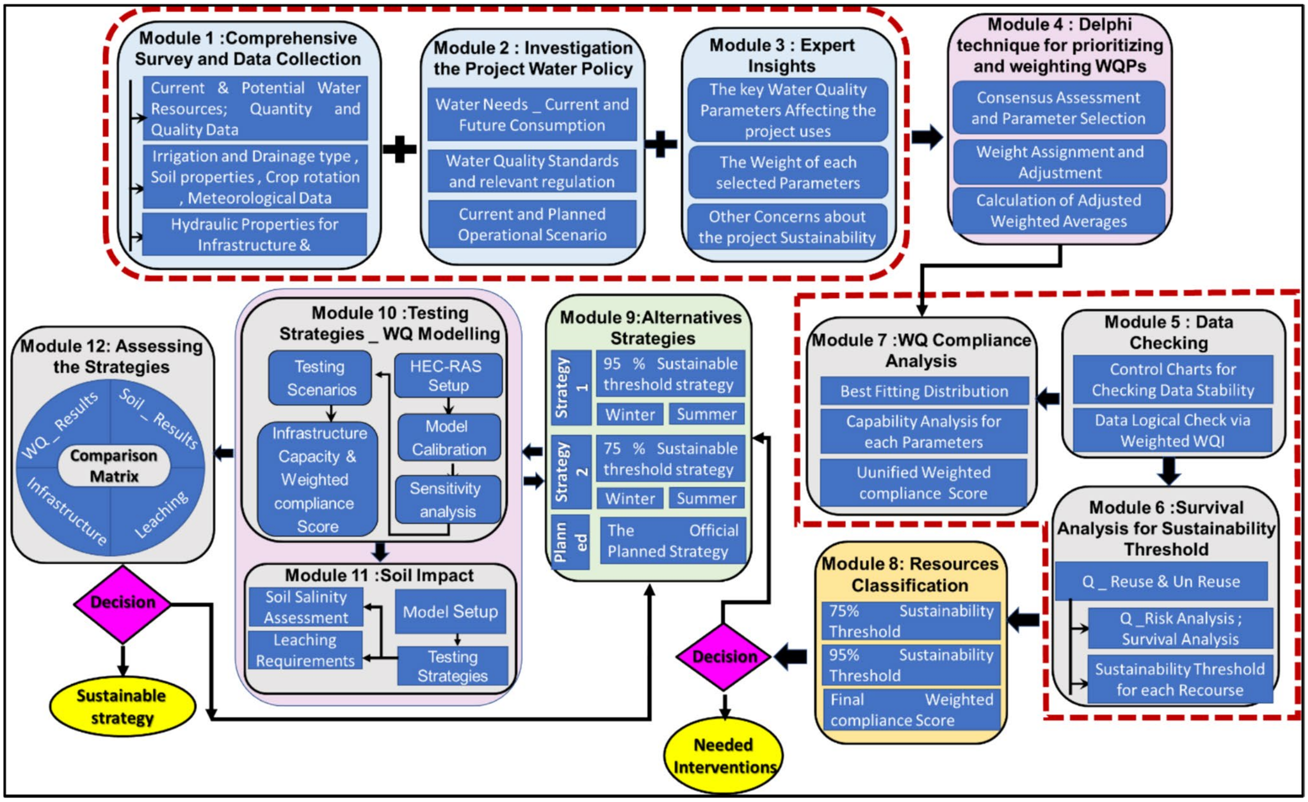

Fig. 1 A multi-model approach for optimizing drainage water reuse sustainability

2025). This sub-model compiles essential datasets across five domains:

- Water resources, encompassing the spatial and temporal characterization of current and potential sources in terms of quantity and quality;
- Soil properties, such as salinity levels, hydraulic conductivity, texture, and physicochemical traits relevant to salt transport and retention;
- Agricultural practices, including cropping patterns, rotation schemes, and cultivation methods; and Meteorological conditions, covering rainfall, temperature, humidity, wind speed, and evapotranspiration.

This integrated dataset forms the foundation for classifying water sources, constructing operational scenarios, and simulating their hydrological and agronomic impacts (Lian et al. 2022).

Module 2: assessment of water policy and operational scenarios

This module evaluates current and projected water demands in relation to the project's water policy and the applicable national regulatory standards governing water quality and quantity. The analysis includes documentation of existing and planned operational scenarios, developed in coordination with project stakeholders to ensure institutional relevance and practical feasibility. By aligning policy frameworks with projected resource needs and quality thresholds, this phase provides critical input for model calibration and supports the formulation of sustainable, regulation-compliant operational strategies tailored to the project's management goals (Abou Jaoude et al. 2022).

Module 3: expert-based prioritization of water quality parameters

This module plays a pivotal role in ensuring that water quality assessments are context-specific and decision-relevant. Within the multi-model framework, expert elicitation is used to assign relative weights to key water quality parameters (WQPs), reflecting their functional importance in the intended reuse application (Tosic et al. 2013).

A structured questionnaire was distributed to a panel of 20 experts comprising: five irrigation specialists from the Water Management Research Institute (WMRI) and Drainge Research Institute (DRI), six soil scientists from Water and Environment Research Institute (SWERI) and DRI, five water quality researchers from academic institutions (Suez Canal University and Zagazig University), and four environmental experts from DRI and Wageningen University. Panel members were selected based on: (i) a minimum of 10 years of professional experience in water reuse or irrigation management, (ii) documented research publications in water quality assessment, and (iii) direct field experience in the Nile Delta or Sinai Peninsula. This multidisciplinary composition ensures comprehensive coverage of agronomic, pedological, and water quality perspectives relevant to the study context.

The expert's responses were then translated into quantitative weights, enhancing the relevance and precision of the sustainability evaluation. By embedding expert insights into the framework, this module ensures that subsequent modeling and scenario analysis are not only technically sound but also aligned with practical management priorities, making it a foundational component of the decision-support architecture (Franciosi et al. 2020).

Module 4: Delphi-based weighting of water quality parameters

This module refines expert input into a consistent and representative weighting system for water quality parameters (WQPs), using a modified Delphi approach tailored to the study's reuse objectives. Based on histogram analysis, only parameters cited by at least 15 experts were retained, resulting in a final set of 11 WQPs. To evaluate the consistency of expert judgments, the interquartile range (IQR) was computed for each retained parameter. All IQR values were below 1.0 on a five-point Likert scale, indicating strong agreement and high reliability of expert scoring. While this consensus-based filtering enhanced analytical focus, it also led to a partial reduction in the total weight originally assigned by each expert due to the exclusion of less frequently selected parameters.

To address this, for each expert k, the sum of weights assigned to the retained parameters $W_{\text{sum, k}}$ through Eq. 1:

$$W_{sum,k} = \sum_{i=1}^{11} W_{ik} \tag{1}$$

Since, the $W_{\text{sum, k}} < 1.0$, the residual weight (R_k) is calculated by Eq. 2: $R_k = (1 - W_{sum,k})$ Eq. 2. To preserve the expert's original weighting intent, this residual is redistributed proportionally across the retained parameters using the Eq. 3:

$$W_{ik,adj} = w_{ik} + \left(\frac{w_{ik}}{W_{sum,k}} * R_k \right) \tag{3}$$

This adjustment ensures that W = 1.0, then the final weight for each parameter ($W_{\text{i, final}}$) is calculated as the mean of the adjusted weights across all experts who rated it (typically 15 experts) using the Eq. 4:

$$W_{i,final} = \frac{1}{15}\sum_{k=1}^{15} W_{ik,adj} \tag{4}$$

This method ensures that only highly corroborated parameters are retained, while preserving the full weight structure of expert input. It enhances the precision and fairness of the weighting process, enabling the aggregation of WQPs into a single compliance index per drainage water source. This index supports water resources classification, scenario comparison and strengthens the decision-making process for sustainable reuse planning.

Module 5: preliminary validation of water resources data

This module implements a two-stage quality assurance protocol to verify the stability and logical consistency of water resources monitoring data prior to advanced modeling and scenario development (Harmel et al. 2023). The first stage employs statistical control charts (Shewhart charts) to detect anomalies and assess the temporal stability of recorded parameters. For a given variable X_t recorded at time t, control limits are set as:$UCL = \mu + 3\boldsymbol{\delta}$, $CL = \mu - 3\boldsymbol{\delta}$**,** where μ is the sample mean and σ is the standard deviation of the dataset. Measurements falling outside the control limits indicate potential outliers or changes in data-generating processes requiring investigation (Shaban 2014).

Subsequently, Water Quality Indices (WQIs) were computed and compared against expected patterns of water mixing and quality attenuation to assess data spatial coherence, as water flows downstream and undergoes sequential mixing, WQI values are theoretically expected to decrease, reflecting cumulative degradation (El-Sayed & Shaban 2019), it is theoretically expected that the WQI should progressively decrease, reflecting cumulative water quality degradation. If the calculated WQI values follow this expected trend, the dataset is considered logically consistent; significant deviations from this pattern may indicate potential data inconsistencies or anomalies requiring further investigation. For each monitoring location, WQI is computed as: $WQI = \sum_{i=1}^{n} w_i * S_i$, where w_i is the expert-adjusted weight for parameter *I* and *Si* is its average measured value.

This validation step is essential, as water quality datasets exhibit unique variability and require tailored verification protocols to ensure reliability and analytical integrity (Karim et al. 2025).

Module 6: reliability-based estimation of sustainable water availability

This module applies survival analysis to estimate water availability thresholds under uncertainty, enabling the formulation of operational scenarios with defined levels of sustainability. The approach ensures that both risk and reliability are explicitly incorporated into water resource planning (Shah et al. 2024). Observed hydrological time series for each water source were analyzed using EasyFit V.5 software. The software automatically tested 70 statistical distributions (e.g., Normal, Log-Normal, Gamma, Weibull) and selected the optimal fit based on goodness-of-fit metrics. For each individual water source, the sustainability threshold Q_p was calculated as the quantile of the fitted distribution corresponding to a specified exceedance probability P_{ex}:

$$Q_p = F^{-1}(P_{ex}) \tag{5}$$

where F(x) is the cumulative distribution function (CDF) of the selected model, and $Q_{(p)}$ represents the flow or yield value that is not exceeded in P_{ex} proportion of time.

Two key thresholds were computed for each source:

- $Q_{0.75}$: Water quantity available with 75% reliability (i.e., exceeded in 75% of the time).
- $Q_{0.95}$: Water quantity available with 95% reliability (i.e., exceeded in 95% of the time).

To account for seasonal variability, the 75% reliability scenario was further disaggregated into summer and winter sub-scenarios, reflecting distinct hydrological conditions and operational constraints. This seasonal differentiation ensures that classification outcomes remain realistic and context-sensitive across temporal variations. This method allows for source-specific quantification of sustainable water volumes under defined reliability levels. It supports the design of resilient and risk-aware operational strategies, ensuring that water reuse planning is both realistic and robust under hydrological uncertainty.

Module 7: water quality compliance analysis

This submodel provides a post-survival analysis evaluation of each water source's compliance with regulatory and project-specific water quality standards. It uses capability analysis to quantify the probability of exceedance for each parameter based on its fitted distribution (Sediyama et al. 2023). The capability index ($C_{pk,\ i}$) for parameter *i* can be defined as:

$$C_{pk,i} = \min\left(\frac{L_i - u_i}{3\delta_i}, \frac{U_i - u_i}{3\delta_i}\right) \tag{6}$$

where L_i and U_i are the lower and upper regulatory limits, μ*i* is the mean, and *σi* is the standard deviation of the observed data for parameter *i*.

Each index is then weighted using the final adjusted weights derived from expert input in Module 4, producing a compliance sub-score (CS_i) using: $CS_i = W_{i,final} * C_{pk,i}$. Then The unified Water Quality Compliance score (W_{QCI}) is determined by aggregating these scores across all parameters:

$$W_{QCI} = \sum_{i=1}^{n} CS_i$$

where *n* is the total number of selected parameters. This unified weighted score provides a single, interpretable indicator of overall water quality per source, facilitating direct comparison across alternatives. It prevents misleading conclusions that may arise from high compliance in less critical parameters or from minor deviations in highly influential ones, thereby supporting more accurate, impact-driven prioritization for sustainable reuse planning.

Module 8: water resources classification

This sub-model functions as an integrative decision-support tool, consolidating outputs from water quantity analysis (Module 6) and water quality compliance evaluation (Module 7) into a unified classification matrix. Specifically, it combines the sustainable yield thresholds estimated at 75% with seatonal variation (summer and winter) and 95% reliability levels with the final weighted Water Quality Compliance Index (WQCI) to enable structured ranking of water sources. This dual-water resources classification, enhanced by seasonal breakdown, supports robust policy evaluation, resource prioritization, and optimized allocation decisions in the context of sustainable and resilient water reuse management (Heidarigharehsoo & Saidi 2023).

Module 9: setting alternatives strategies

This sub-model builds directly on the classification outcomes from Module 8, integrating both water quantity thresholds (from Module 6) and water quality compliance scores (from Module 7) to formulate operational strategies that meet the project's future water requirements. Three scenarios were developed: two proposed management strategies and one official project scenario. Each scenario aims to ensure sufficient water delivery to the intake point, while accounting for variability in both quantity and quality. A key principle guiding scenario design is the inverse relationship between sustainability thresholds and available water quantities:

- The Planned Scenario (Baseline) represents the official operational plan established by project operators
- The 75% water supply reliability scenario is based on water volumes available with 75% reliability, offering higher yield but lower certainty.
- The 95% water supply reliability scenario reflects more conservative planning, using volumes available with 95% reliability, ensuring higher certainty but lower yield.

While a water source may appear more favorable under the 75% scenario due to higher available volumes, this does not indicate superior sustainability, only reduced reliability. To account for seasonal variability, the 75% reliability scenario was further disaggregated into summer and winter sub-scenarios, capturing distinct hydrological conditions and operational constraints. This structured, seasonally informed framework enables adaptive, risk-aware planning and enhances the El-Salam Canal project's operational resilience under fluctuating hydrological and regulatory conditions.

Module 10: testing strategies; water quality modelling

This module simulates and evaluates the hydraulic and water quality performance of each alternative strategy using the HEC-RAS modeling system, developed by the U.S. Army Corps of Engineers. Given the unidirectional flow and intermittent siphons along the El-Salam Canal, a one-dimensional unsteady flow approach is adopted to assess conveyance capacity and dynamic water quality behavior (Zainal & Talib 2024).

HEC-RAS provides an integrated platform for simultaneous simulation of hydraulic flow and constituent transport. The model incorporates detailed canal geometry and applies initial and boundary conditions for both flow and water quality parameters. Simulations are governed by the continuity and momentum equations, enabling spatial and temporal resolution of system dynamics. The water quality module employs the QUICKEST-ULTIMATE explicit scheme to solve the one-dimensional advection–dispersion equation, capturing pollutant transport, transformation, and decay. Simulated parameters include: DO, pH, TDS, COD, BOD_5, TSS, NH_3, TN, Cl^-, and TP. This modeling framework enables robust testing of each strategy's capacity to meet water quality objectives under realistic hydraulic and pollutant loading conditions.

Module 11: soil impact modelling

This module quantifies the impact of alternative water management strategies on soil salinity dynamics, leaching requirements, and the long-term sustainability of irrigated agriculture using the physically based SWAP (Soil–Water-Atmosphere-Plant) model. SWAP is a widely validated tool for simulating water flow and solute transport in variably saturated soils under diverse irrigation regimes, meteorological conditions, and soil profiles (Jiang et al. 2011). Water movement within the soil profile is governed by the Richards equation (Warrick et al. 1990), while soil hydraulic properties are described using the van Genuchten–Mualem parameterization (Genuchten 1980):

$$\theta\left(h\right)=\theta_r+\frac{\theta_s-\theta_r}{\left(1+\left(\alpha*h\right)n\right)m} \tag{7}$$

$$K\left(h\right)=K_s*S_e^1\left(1-\left(1-S_e^{\frac{1}{m}}\right)m\right) \tag{8}$$

where, θ*s* and θr are saturated and residual water content respectively, Ks is saturated hydraulic conductivity, *Se* is effective saturation, and parameters α, n, m, and l encapsulate pore-size distribution and connectivity effects (Genuchten 1980).

Salinity transport is modeled via the convection–dispersion equation, accounting for advection, diffusion, and root uptake:

$$\frac{\partial(C\theta)}{\partial t}=\frac{\partial}{\partial z}\left(D\left(\theta\right)\frac{\partial C}{\partial z}-q^C\right)-S_C \tag{9}$$

where C is solute concentration [mg/L], D(θ) the dispersion coefficient [cm^2/day], q the Darcy water flux [cm/day], and *Sc* represents solute sinks.

To assess salinity stress, the leaching requirement (LR) is calculated using Eq. 10:

$$LR=\frac{EC_{iw}}{5*EC_e-EC_{iw}} \tag{10}$$

where $\mathrm{EC}_{\mathrm{iw}}$ is the electrical conductivity of irrigation water, and ECe is the target soil salinity threshold (Dudley et al. 2008).

Crucially, the salinity levels of irrigation water derived from Module 10 are used as inputs here to evaluate their downstream effects on soil health and crop productivity. This allows for a comprehensive assessment of each operational scenario, not only in terms of water quality and quantity, but also in terms of soil sustainability and leaching demands, which directly influence long-term agricultural viability.

Module 12: comparison matrix for the strategies visualization

This module consolidates both quantitative and qualitative outputs from preceding components into a unified comparison matrix, enabling structured visualization and evaluation of all examined strategies. To ensure clarity and transparency, the comparison matrix presents the evaluation results across all sustainability dimensions without applying explicit weighting or prioritization among criteria.

This approach reflects the observed coherence between indicators: strategies that achieve higher water quality compliance also tend to exhibit lower soil salinity, reduced leaching requirements, and minimal infrastructure needs. As such, the best-performing scenario consistently excels across all dimensions, allowing for straightforward interpretation without the need for trade-offs or subjective preference weighting. The matrix thus serves as a transparent tool for organizing results and facilitating direct comparison, rather than negotiating between competing objectives.

Materials and methods

Case study; El-salam Canal project

Arid and semi-arid regions face mounting pressures from water scarcity, salinity accumulation, and competition for freshwater resources, making drainage water reuse (DWR) an essential adaptation strategy across North Africa, the Middle East, and South Asia (Mateo-Sagasta et al. 2023). However, its sustainability remains constrained by challenges including salinity buildup, nutrient imbalances, and limited treatment capacity (Qureshi & Perry 2021). El-Salam Canal project in Egypt was selected as a representative case study because it exemplifies these broader regional challenges. As one of the largest DWR initiatives in the Middle East, the project operates under the same constrained hydrological and environmental conditions characteristic of arid zones, making it a suitable model for evaluating integrated water-soil management strategies (Abdel-Azim & Allam 2005).

Originally designed to deliver approximately 4.45 billion cubic meters per year of blended water, the El-Salam Canal system operates on a planned 1:1 mixing ratio between freshwater from the Nile's Damietta branch and drainage water from Bahr Hadus and El-Serw drains (Shaban & El sayed 2012). This blended supply was intended to support the reclamation of nearly 620,000 acres of agricultural land located on both the eastern and western sides of the Suez Canal. The canal system is hydraulically divided into two main reaches: the western reach, known as the El-Salam Canal, and the eastern reach, referred to as the Sheikh Jaber

Canal, which extends beyond the Suez Canal into the Sinai Peninsula. Figure. 2 illustrates the overall layout of the system and its key water sources.

Despite its strategic importance, El-Salam Canal project faces substantial operational and environmental challenges that directly impact its sustainability. Freshwater allocations have declined, prompting increased reliance on drainage water sources such as the Faraskour drain to support the initial phase of the project (Shaban & El sayed 2012). However, available water resources remain insufficient to initiate the second phase of the North Sinai Agricultural Development Project, which targets the reclamation of 420,000 feddans in Central Sinai instead of the originally planned El-Serw and El-Qawareer areas (Raslan et al. 2020).

The second phase requires a daily water quota of 7.35 million m^3, while current availability at the Sheikh Jaber Canal is limited to 2 million m^3/day, resulting in a deficit of approximately 5.35 million m^3/day. To bridge this gap, the Bahr El-Baqar wastewater treatment plant was commissioned, with a treatment capacity of 5.6 million m^3/day, drawing from Bahr El-Baqar, Om El-Rish, and Shader Azzam drains.

Despite these efforts to secure a water supply, salinity remains the most critical constraint. Elevated salinity levels, particularly following the partial operation of the Bahr El-Baqar plant, have been observed in irrigation water. Additionally, Soil salinity surpassing 7.12 dS/m in parts of the study area limits crop diversity and affects salt-sensitive species. Leaching elevated soil salinity requires a substantial quantity of fresh water, reducing overall system efficiency.

These operational and environmental challenges faced by the El-Salam Canal project are not confined to Egypt but represent systemic constraints prevalent in drainage water reuse schemes globally. Comparable limitations related to salinity management and freshwater scarcity have been documented in major irrigation systems such as Pakistan's Indus Basin, Jordan's Zarqa River (Almanaseer et al. 2020). Consequently, the El-Salam Canal serves as a representative case study for assessing the feasibility and resilience of integrated water-soil management frameworks under arid and semi-arid conditions, with insights that are broadly transferable to similar agro-hydrological systems worldwide.

Data collection and sources

Comprehensive datasets on water quality and quantity were collected between August 2018 and July 2023 from from 18 strategically selected monitoring locations to capture spatial and operational variability across the system. These included:

- One point at the El-Salam Canal Intake,
- Six points representing current and potential drainage water sources,
- Six points along the main canal stream for model calibration,
- Five points associated with the Bahr El-Baqar wastewater treatment plant.

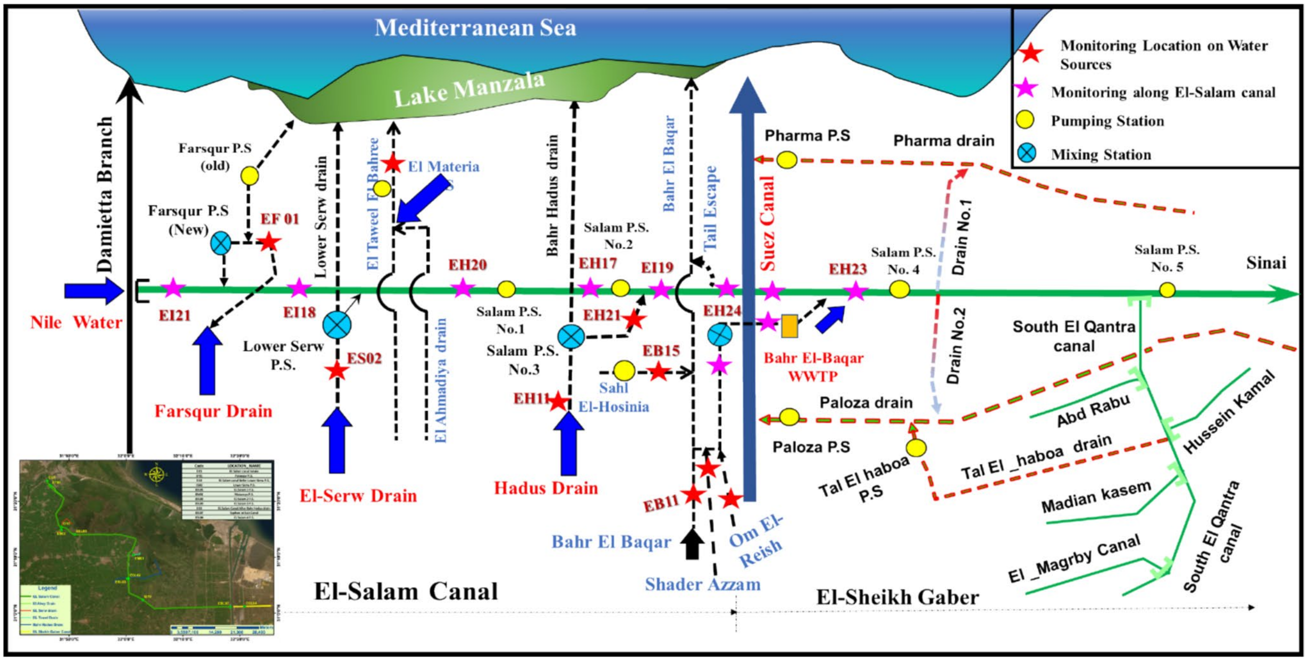

Fig. 2 Scimatic layout of El-Salam Canal project

The selection of monitoring sites was designed to represent key hydrological zones, operational nodes, and inflow sources. All datasets were obtained from the Drainage Research Institute (DRI), part of Egypt's National Water Quality Monitoring Network (NWQMN). Monthly water samples were analyzed in ISO/IEC 17025-accredited laboratories, following internationally standardized protocols to ensure data reliability.

Approximately 15% of samples were designated as replicates for quality assurance, assessed independently in accordance with APHA Section 1020 to verify analytical reproducibility. QA/QC procedures included the use of blanks, certified reference materials, spiked samples, and duplicate analyses. All instruments were regularly calibrated before and during analysis. To ensure data continuity, minor gaps ($<5\%$) in the time series were addressed using linear interpolation, preserving statistical integrity and temporal patterns. Discharge measurements were obtained using Acoustic Doppler Current Profilers (ADCP) in open channels and from pump station operational logs.

To assess soil response to irrigation water quality, soil samples were collected in June 2024 from five distinct locations within the Sheikh Jaber Canal command area, targeting two depths (0–40 cm and 80–120 cm). These samples were analyzed for texture, salinity, and ion composition in accordance with ASTM D4972 and D2216 standards, ensuring spatial representativeness for soil impact modeling. Complementary datasets were obtained from the North Sinai Water Resources and National Infrastructure Sector, including information on irrigation methods, water scheduling, drainage configurations, and crop rotation patterns.

Water quality regulation standards

The El-Salam Canal project adheres to a multi-tiered regulatory framework to ensure safe reuse of drainage water. Central to this is Article 51 of Law No. 48 (2013), which mandates strict quality standards for agricultural drains, such as Hadous, Faraskour, and El-Serw, before blending with freshwater. Additionally, effluent from the Bahr El-Baqar WWTP is evaluated against design specifications before discharge into the Sheikh Jaber Canal. The project also aligns with FAO irrigation water quality guidelines, supporting crop safety and long-term soil productivity across canal reaches (Agrama & Amer 2012).

Current and planned operational scenario

In the current operational scenario (Fig. 3), El-Salam Canal system receives a total inflow of approximately 110 m^3/s from multiple sources. The primary input is a constant 38.0 m^3/s from the Nile's Damietta Branch, supplemented by: 8.0 m^3/s from the Faraskour Drain (km 1.9), 19.0 m^3/s from the El-Serw Drain (km 18.5), 33.0 m^3/s from the Hadous Drain (km 54.0), and 13.0 m^3/s from the Bahr El-Baqar Wastewater Treatment Plant (WWTP). Of this total, 77 m^3/s is allocated to the western side of the Suez Canal, supporting irrigation over approximately 200,000 feddans. The remaining 33.0 m^3/s (equivalent to 2.85 million m^3/day)

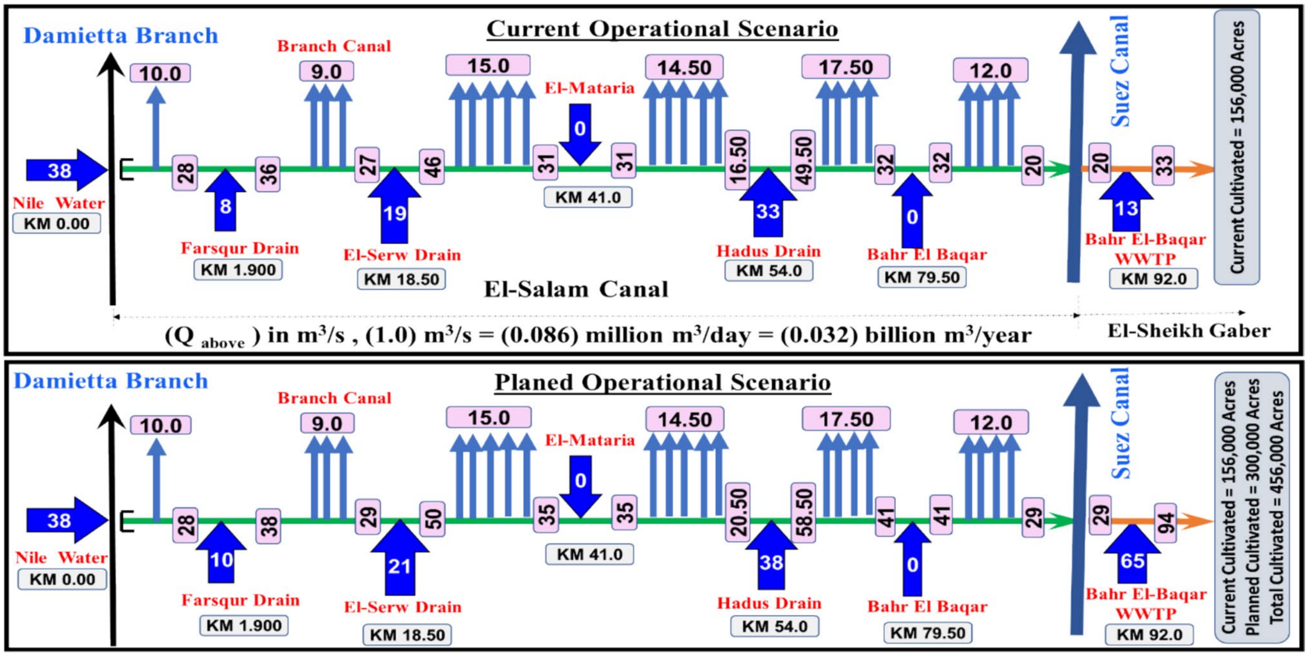

Fig. 3 Current and planned operational scenarios for the El-Salam Canal system

is delivered to lands served by the Sheikh Jaber Canal, covering around 156,000 acres, with a water duty of 30.0 m^3/feddan/day.

To implement the second phase of the El-Salam Canal project, targeting the reclamation of an additional 420,000 feddans, the Ministry of Water Resources and Irrigation has developed a planned operational scenario to meet the significantly increased water demand of about 94.0 m^3/s (equivalent to 8.12 million m^3/day). This scenario involves scaling up inflows, as illustrated in Fig. 3, by approximately 95% of the additional supply is expected to come from the Bahr El-Baqar WWTP, with only marginal increases from other sources.

Numerical models setup and calibrations

HEC-RAS model

The HEC-RAS V.5 model was employed to simulate the hydraulic behavior and water quality dynamics of the El-Sheikh Jaber Canal system under multiple operational scenarios, including current conditions, officially planned operations, and proposed management alternatives. All relevant inflows from branch channels and feeder sources were incorporated as point-source inputs, while the downstream boundary condition was defined by the water level downstream of the Salam 4 pumping station, maintained at 0.40 m.

The model was driven by measured operational discharge data, enabling realistic simulations of flow patterns and water quality transport. Model accuracy was evaluated using the Root Mean Square Error (RMSE), calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2}$$

where O_i and S_i are the observed and simulated values respectively, for *n* observations.

Calibration was conducted through iterative refinement, comparing simulated water levels against field measurements at eight monitoring sites along the El-Salam and Sheikh Jaber canals. Manning's roughness coefficients were adjusted across canal reaches to optimize model performance, resulting in a final RMSE of 0.054 m, indicating a high level of hydraulic accuracy. Following hydraulic calibration, the model was supplied with measured water quality parameters (WQPs) including SAR, TDS, pH, NO_3, Cl, BOD, COD, TP, Boron, TSS, and Fe, along with relevant meteorological and dispersion coefficients for each inflow source and the canal intake. Initial simulations were conducted under the baseline operational scenario to establish reference conditions.

Water quality calibration was performed by comparing observed and simulated WQPs at five monitoring locations along the El-Salam Canal, focusing on key indicators: TDS, DO, BOD, TSS, N–NO_3, and TP, as illustrated in Fig. 4.

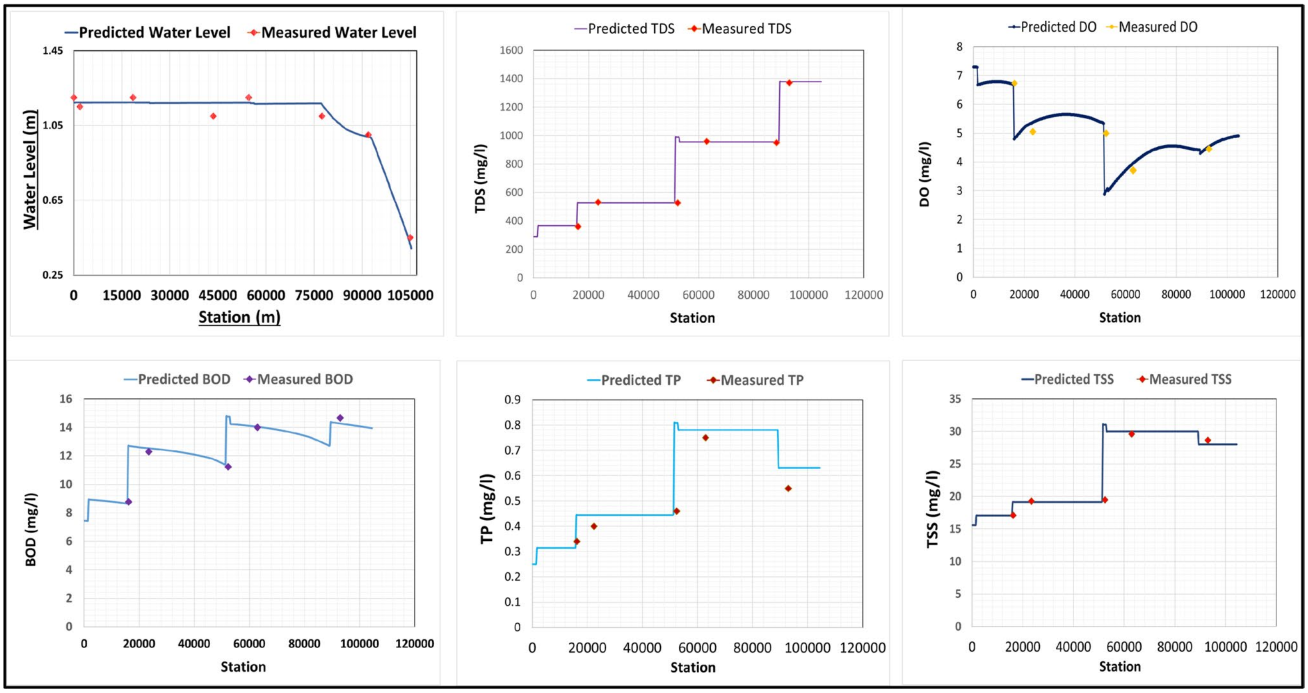

Fig. 4 Hydraulic and water quality calibration along El-Salam Canal

Table 1 Spatial distribution of soil sampling sites

Sample no	Coordinates (decimal degrees)		Canal position
	Latitude	Longitude	
1	31.0350	32.3680	Main canal/Left Bank
2	30.9989	32.4657	Branch canal/Right Bank
3	31.0026	32.3973	Main canal/Right Bank
4	30.9526	32.4763	Branch canal/Right Bank
5	31.0205	32.5017	Main canal/Right Bank

The model's predictive performance was evaluated using both Root Mean Square Error (RMSE) and the coefficient of determination (R^2). Root Mean Square Error (RMSE) values consistently low relative to the observed ranges; RMSE $_{DO}$ = 0.091 within an observed range of 4.0 mg/L, RMSE $_{TDS}$ = 2.07 within a range of 1100 mg/L, RMSE $_{BOD}$ = 0.085 within a rang of 7.0 mg/L, RMSE $_{TSS}$ = 0.13 within a range of 15.0 mg/L, RMSE $_{N\text{-}NO3}$ = 0.0119 within a range of 7.0 mg/L, and RMSE $_{TP}$ = 0.016 within a range of 0.55 mg/L.

Complementing these results, the model achieved R^2 values exceeding 0.83 for all calibrated parameters, reflecting the model's robustness in capturing both the spatial variability and temporal dynamics of water quality along the canal system, making it suitable for scenario-based assessments and operational planning.

SWAP model

Soil characterization and hydraulic properties Soil samples were collected from five spatially distributed locations (Table 1) representing the dominant land use types and salinity gradients within the Sheikh Jaber Canal catchment, strategically selected using stratified random sampling to achieve three objectives: (1) comprehensive representation of the entire canal command area from the main intake (El-Salam Canal) through downstream reaches, including both right and left banks of the main canal and the primary South Qantara branch canal; (2) coverage of approximately 85% of the historical salinity variability across the study area based on previous surveys (Measured by Drainage Research Institute 2017); and (3) capture of spatial gradients in proximity to irrigation canals (0–1000 m vs. 1000–2000 m).

At each location, samples were collected from two depth intervals (0–100 cm and 100–150 cm) using a soil auger. Samples were immediately sealed in airtight containers, subsequently air-dried, crushed, and sieved through 2-mm mesh to remove coarse fragments and organic debris. Particle size distribution was determined using the hydrometer method, validated by sieve analysis for sand fractions, following FAO guidelines. Textural analysis classified all samples as sandy loam as illustrated in Table 1. Saturated hydraulic conductivity (Ks) was measured (Table 1), using the constant-head permeameter method on undisturbed cores, following standardized protocols. These data served as inputs for the Rosetta pedotransfer function model to estimate van Genuchten hydraulic parameters (Table 2).

In addition, soil salinity was assessed by measuring the electrical conductivity (ECe) of saturated paste extracts at both depths (40 cm and 120 cm) for all five sampling locations. Measurements were conducted at the Central Laboratory for Environmental Monitoring (CLEQM), ensuring analytical consistency and quality control (Table 2).

Crop parameterization The crop composition in this study includes wheat (Triticum aestivum L.) and maize (Zea mays L.), two primary cereal crops cultivated in Sinai Peninsula. Crop parameters were calibrated to regional field conditions, incorporating rooting depth dynamics, leaf area index (LAI) progression, and salinity-based yield response functions (Table 2). Maximum rooting depths were set at 90 cm for wheat and 120 cm for maize, consistent with observed root penetration in sandy loam soils (Whalley et al. 2021), (Leenaars et al. 2023).

Peak LAI values of 4.5 for wheat and 5.2 for maize were adopted from published field studies in similar agro-climatic zones (Buthelezi et al. 2023), enabling accurate simulation of evapotranspiration and photosynthetic

Table 2 Sandy loam soil hydraulic properties and texture

Sample no	Depth (cm)	Measured EC (ds/m)	Sand (%)	Silt (%)	Clay (%)	van Genuchten α (cm − 1)	n	θr	θs	Ks (cm/d)
1	0–100	5.45	70	20	10	0.034	2.58	0.063	0.42	106
	100–150	6.15	73	17	10	0.036	2.65	0.061	0.38	118
2	0–100	5.63	69	20	11	0.034	2.55	0.068	0.41	98
	100–150	6.25	74	19	7	0.035	2.64	0.066	0.40	124
3	0–100	6.55	65	20	15	0.031	2.53	0.074	0.42	93
	100–150	7.12	69	21	10	0.033	2.70	0.069	0.42	100
4	0–100	5.55	74	16	10	0.036	2.63	0.066	0.41	119
	100–150	5.75	72	17	11	0.038	2.67	0.059	0.39	120
5	0–100	5.10	69	19	12	0.033	2.63	0.070	0.42	103
	100–150	5.35	75	14	11	0.036	2.63	0.067	0.42	115

activity within the SWAP framework (Huang et al. 2024). Salinity tolerance parameters followed FAO-56 guidelines, with threshold electrical conductivity (ECe) values of 2.5 dS/m for wheat and 3.0 dS/m for maize. Yield reduction slopes were set at 11%/dS/m and 8%/dS/m, respectively (Steppuhn, H., & Grieve 2004). Mid-season crop coefficients (Kc) of 1.1 for wheat and 1.15 for maize reflect peak transpiration demands under Mediterranean climates (SHARMA et al. 2024).

Additional SWAP model parameters were specified to enable complete model reproduction. Initial rooting depth was set at 10 cm for both crops at emergence, progressing to maximum depths reported in Table 2. Crop coefficients for all growth stages (Kc_ini = 0.30 and 0.40; Kc_mid = 1.10 and 1.15; Kc_end = 0.30 and 0.50 for wheat and maize, respectively) were adopted from FAO-56 guidelines. Water stress response was governed by two critical pressure head thresholds: $h3 = -300$ cm, representing the onset of transpiration reduction under moderate soil water depletion, and $h4 = -700$ cm, defining the wilting point beyond which root water uptake ceases. These values were calibrated to the sandy loam soil hydraulic properties (Table 2).

Meteorological inputs Daily meteorological data, including rainfall, temperature, solar radiation, and wind speed, were obtained from the ERA5 climate reanalysis dataset (ECMWF, 1979–present). ERA5 provides comprehensive atmospheric variables at $0.25° \times 0.25°$ spatial resolution (~25 km) with hourly temporal resolution. Hourly data were aggregated to daily values for model input. ERA5 has been extensively validated for Egyptian conditions, demonstrating strong agreement with in situ observations.

Irrigation management Drip irrigation scheduling was implemented using soil water pressure head–based triggering consistent with local field practices. For wheat, irrigation was triggered when pressure head at 20–25 cm depth fell below − 500 to − 600 cm; for maize, the trigger threshold was − 300 to − 400 cm at 30 cm depth. Individual applications delivered 45–55 mm for wheat and 50–60 mm for maize over 4–7-h durations, with 2–5-day intervals between events depending on growth stage. This resulted in 11–13 irrigation events for wheat (580–620 mm total) during November–April, and 11–13 events for maize (620–660 mm total) from May to September, accounting for both crop water requirements and leaching needs under moderately saline conditions.

Model setup and boundary conditions Initial conditions were derived from field measurements at crop establishment. Soil moisture was set at field capacity in the upper profile, decreasing with depth according to observed hydraulic gradients. Root-zone electrical conductivity showed vertical stratification, averaging 5.65 dS/m at 40 cm depth and 6.12 dS/m at 120 cm depth, representing moderately to highly saline conditions typical of the Eastern Suez Canal region. The upper boundary incorporated measured precipitation and applied irrigation fluxes with their respective salinity levels. The lower boundary was positioned at 200 cm depth and configured for free drainage (unit hydraulic gradient condition), reflecting deep water table conditions (> 3 m) documented in regional hydrogeological surveys. These initial conditions enabled realistic simulation of coupled water and salt dynamics under prevailing field conditions.

Model calibration and validation The SWAP model was calibrated using observed soil salinity profiles obtained from representative sandy loam soils within the Sheikh Jaber Canal catchment, east of the Suez Canal. Field measurements indicated average electrical conductivity (ECe) values of 5.65 dS/m at 40 cm depth and 6.12 dS/m at 120 cm depth, reflecting moderately saline conditions typical of the study area. Simulated root-zone salinity under baseline conditions yielded an average EC of 5.92 dS/m, with a root mean square error (RMSE) of 0.27 dS/m and a coefficient of determination (R^2) of 0.89, indicating excellent agreement between observed and simulated values.

The calibration assumed spatially uniform soil properties due to limited sampling density across the catchment. Field observations, however, indicated moderate spatial variability in soil salinity, with coefficients of variation (CV) ranging from 15 to 25% across sampling locations. This heterogeneity reflects natural variations in soil texture, hydraulic conductivity, and localized drainage patterns commonly found in sandy loam agricultural systems. Despite this simplification, the strong model data agreement (RMSE = 0.27 dS/m, $R^2 = 0.89$) demonstrates that the model adequately captures the dominant processes. The comparative scenario analysis also remains valid, as all alternatives were assessed under the same modeling assumptions.

Nevertheless, in cases where horizontal soil heterogeneity is more pronounced, adopting advanced two-dimensional models such as HYDRUS-2D would be necessary. HYDRUS-2D can simulate variably saturated flow and solute transport in two dimensions, providing a more detailed spatial representation for heterogeneous soil environments.

Results and discussion

Water quality parameter prioritization and weighting

By applying Modules 3 and 4, A structured Delphi approach involving 20 qualified experts identified 11 critical water quality parameters that affect the sustainability of agricultural reuse. Parameters achieving ≥ 75% expert consensus were retained and weighted based on normalized mean scores, with expert agreement validated by interquartile range (IQR < 1.0). The finalized weighting scheme (Table 4) reveals that (TDS) and (SAR) are the most influential parameters, with weights of 0.21 and 0.20, respectively. These high weights reflect their dominant influence on soil structural stability and long-term irrigation sustainability, consistent with recent expert assessments (Machado & Serralheiro, (2017), (Dudley & State 2008).

The prioritization of SAR aligns with its documented effects on clay dispersion and reduction in hydraulic conductivity of fine-textured soils. TDS directly affects osmotic stress and plant water uptake capacity. Nitrate (0.11) ranks third, reflecting dual concerns regarding the potential of groundwater contamination and excessive vegetative growth under high nitrogen loading. Moderate weights assigned to pH, chloride, and BOD (0.08 each) indicate their secondary but non-negligible roles in soil chemistry and microbial activity. Conversely, Total Suspended Solids (TSS) received the lowest weight (0.02), likely reflecting the relatively low suspended solid concentrations typical of subsurface drainage systems in the study region.

These results confirm FAO guidelines emphasizing salinity (TDS, SAR) as primary DWR constraints in arid regions, while the low TSS/Fe weights reflect the predominance of subsurface drainage inputs over physical clogging risks in El-Salam. Nitrate's third-place ranking highlights emerging groundwater contamination concerns, underscoring the need for integrated salinity-nutrient management. This expert-derived weighting therefore does not merely rank parameters but also reveals the implicit risk perception that shapes practical reuse decisions in large-scale Egyptian schemes.

Table 3 Crop parameterization for wheat and maize in SWAP model

Parameter	Wheat (*Triticum aestivum L.*)	Maize (*Zea mays L.*)
Maximum rooting depth (cm)	90	120
Initial rooting depth (cm)	10	10
Leaf area index (LAI) Peak	4.5	5.2
Salinity threshold ECe (dS/m)	2.5	3.0
Yield reduction Slope (%/dS/m)	11	8
Crop coefficient (Kc—ini)	0.30	40
Crop coefficient (Kc—mid)	1.1	1.15
Crop coefficient (Kc—end)	0.30	0.50
Water stress response (Reduction begins (cm))	− 300	− 300
Water stress response (Wilting point (cm))	− 700	− 700
Growing season	November–April	April–September

Preliminary data checking

Water source statistical stability assessment

Statistical stability of water quality data is essential for reliable long-term operational planning in large-scale reuse projects. Control charts were constructed for each water quality parameter across the five primary water sources, with control limits set at ± 3 standard deviations to identify outliers while capturing natural variability. For each source, weighted deviations beyond control limits were calculated using the parameter importance coefficients from Table 3, yielding a cumulative data consistency score (100% minus weighted deviations).

The results indicate that all sources maintained acceptable statistical stability, with Bahr El-Baqar WWTP exhibiting the highest consistency (99.65%), followed by Hadous Drain (99.50%) and Faraskur Drain (95.29%). Moderate stability was observed at El-Matariya Pumping Station (92.72%), while Bahr El-Baqar Drain exhibited the lowest score (90.75%). Source stability differences reflect inherent uncertainty characteristics: managed point sources (Bahr El-Baqar WWTP) show low variability due to controlled operations, while Bahr El-Baqar Drain exhibits higher uncertainty from hydrological fluctuations and diffuse pollution. These patterns were incorporated into subsequent analyses, with all sources confirming data reliability for compliance assessment and scenario modeling.

Data spatial consistency validation

Data validation was performed to confirm spatial consistency along the canal system. Given the progressive blending of Nile water with drainage water downstream, water quality is expected to deteriorate sequentially after each mixing point. To verify this pattern, the Water Quality Index (WQI) was calculated using the expert-weighted parameters from Table 3, at six monitoring location along the El-Salam Canal (Jo et al. 2024).

Results confirmed the anticipated downstream degradation trend: WQI decreased progressively from 76.50 at the canal intake (pre-mixing) to 72.63 after Faraskur Drain, 65.40 after El-Serw Drain, 63.72 before Hadous confluence, 55.30 after Hadous Drain, and 52.25 following Bahr El-Baqar WWTP effluent addition. This systematic decline, reflecting the cumulative impact of drainage inputs weighted by their relative importance, validates the spatial coherence of the dataset and confirms its suitability for subsequent analytical modules. The monotonic WQI decline confirms the current operations approach marginal quality at downstream areas, validating the need for scenario-based optimization to improve rather than redistribute pollution.

Water availability assessment under reliability thresholds

Following data validation, the water quantity analysis focused on assessing current reuse levels and estimating sustainable availability under different reliability scenarios. Average reused quantities, total discharge, and reuse ratios were calculated for each drainage source feeding the El-Salam Canal. Current reuse patterns (Table 4) reveal substantial variability across sources. Faraskur drain exhibits a moderate reuse rate (52.0%), while Hadous and El-Serw drains demonstrate higher utilization (57.0% and 67.0%, respectively). Notably, El-Matariya Pumping Station, receiving flow from El-Ahmadia, Al-Tawel El-Qebly, and Al-Tawel El-Bahry drains, currently shows zero reuse despite substantial discharge capacity (average 24.33 m^3/s), indicating significant potential for future expansion.

Survival analysis was applied to estimate water availability at 75% and 95% reliability thresholds, representing flow rates expected to be available under normal and dry-year conditions, respectively. Results (Table 5) reveal pronounced seasonal variability. Hadous Drain, for example, maintains an annual average of 60.0 m^3/s, with 75% reliability flows ranging from 56.0 m^3/s (winter) to 63.66 m^3/s (summer). However, at 95% reliability, availability decreases sharply to 38.50 m^3/s (winter) and 47.25 m^3/s (summer), illustrating the inherent trade-off between reliability level and available volume.

Table 4 Expert-weighted water quality parameters affecting soil and plant health

Parameter	Weight	Parameter	Weight
SAR (Sodium adsorption ratio)	0.20	COD (Chemical Oxygen Demand)	0.06
TDS (Total dissolved solids)	0.21	TP (Total Phosphorus)	0.07
NO3 (Nitrate)	0.11	Boron	0.05
pH	0.08	TSS (Total Suspended Solids)	0.02
Cl (Chloride)	0.09	Fe (Iron)	0.03
BOD (Biological oxygen demand)	0.08	Total	1.00

The results reveal a clear reduction in available volumes at higher reliability thresholds, directly constraining feasible reuse ratios. Additionally, the results emphasize pronounced seasonal dynamics, with lower flows observed in winter and higher flows in summer, underscoring the need for the explicit integration of seasonality into any strategy for water allocation, drainage reuse optimization, and future resource planning.

These findings imply that strategies relying heavily on single high-volume sources without accounting for reliability thresholds are likely to overestimate sustainable reuse potential, especially under dry-year conditions. In particular, the contrast between the apparent abundance of El-Matariya flows and their sharply reduced volumes at 95% reliability illustrates why conventional average-based planning can be misleading. Embedding survival-based availability into the framework therefore ensures that proposed operational scenarios remain robust under hydrologic stress, a requirement that is often overlooked in traditional DWR design.

Water quality compliance assessment

Compliance of each drainage source with regulatory standards was evaluated using process capability analysis integrated with expert-weighted parameters (Table 3). The assessment framework applied Egyptian Law No. 48/1982 (Article 51) and FAO guidelines.

Table 5 El-Salam Canal drainage water resources, status, and survival estimates

Drainage water resources	Reuse ratio	75% sustainability threshold			95% sustainability threshold		
	Q (Reuse)/Q(Total)	Annually	Winter	Summer	Annually	Winter	Summer
Frasqur drain	52%	15.2	13.5	18.0	10.2	8.6	13.6
El-Serw drain	67%	28.6	23.8	33.9	19.0	16.2	26.0
El Mataria P. S	0%	24.9	21.2	28.7	16.0	12.3	19.9
Hadous drain	57%	60.0	56.0	63.7	43.0	38.5	47.0
B. El-Baqar drain	0%	25.0	19.0	27.0	19.5	15.9	24.3
El-Baqar WWTP	21%	64.8	64.8	64.8	63.4	64.8	64.8

The aggregated weighted compliance scores (Table 6) reveal substantial in-compliance variability. Faraskur and El-Serw drains demonstrate excellent overall weighted compliance (99.08% and 97.76%, respectively), with > 93% conformance across all parameters, aligning with international benchmarks for agricultural reuse (FAO, 2021). This high performance is attributable to the fact that both drains serve exclusively agricultural command areas, with minimal industrial or municipal inputs. In comparison, Hadous Drain exhibits good compliance (93.85%), though with moderate deviations in SAR (86%) and NO_3 (85%). Similarly, El-Matariya Pumping Station achieves an acceptable score of (89.03%), but exhibits notable limitations in SAR (63%) and NO_3 (77%) compliance.

Bahr El-Baqar Wastewater Treatment Plant (WWTP) records a moderate compliance score of 79.85%, primarily constrained by elevated salinity. While the plant achieves 100% compliance for organic and nutrient parameters (BOD, COD, TP), TDS compliance remains critically low at 11%, reflecting the inherently saline nature of the influent water. These findings underscore the need for operational strategies such as blending with low-salinity sources and soil leaching practices to maintain root-zone salinity within acceptable thresholds. By contrast, the Bahr El-Baqar Drain exhibits the lowest compliance (47.17%), with severe exceedances in SAR (5%), TDS (20%), NO_3 (37%), and BOD (38%). Bahr El-Baqar Drain's poor compliance reflects multiple pollution sources (domestic wastewater, agricultural runoff, industrial discharges), mirroring heavily-impacted basins like Ganges and Yellow Rivers (Li et al. 2020). While seasonal analysis reveals winter, compliance declines due to reduced dilution versus summer improvements, underscoring the limitations of static assessments and the need for adaptive, time-variable management strategies.

The compliance assessment establishes a clear source prioritization hierarchy. This hierarchy confirms that not all drainage sources should be treated symmetrically in reuse planning: some can safely support direct irrigation, whereas others must be constrained to blending or excluded entirely. In practice, this supports a "tiered" management strategy in which high-compliance drains (Faraskur, El-Serw, Hadous) are prioritized for sensitive crops and soils, while more saline or nutrient-rich sources are reserved for tolerant crops or used primarily as dilution inputs. The strong divergence between Bahr El-Baqar Drain and Bahr El-Baqar WWTP also illustrates the benefits of centralized treatment in partially mitigating, but not fully resolving, upstream salinity problems, highlighting the importance of catchment-scale pollution control in parallel with plant-scale optimization.

Table 6 Weighted compliance assessment for drainage sources

WQPs	WQ Standards	Wight	Farskour		Serw		El Mataria P. S		Hadous		B. El-Baqar		B. El-Baqar WWTP	
			%	Score	%	Score	%	Score	%	Score	%	Score	%	Score
SAR	0—6	0.20	98	19.70	93	18.64	63	12.60	86	17.10	5	0.91	93	18.64
TDS	0—2000	0.21	100	21.00	100	21.00	100	21.00	100	21.00	20	4.29	11	2.21
pH	6.5—8.5	0.08	97	7.76	100	8.00	100	8.00	100	8.00	99	7.94	100	8.00
NO3	0–20	0.11	99	10.92	94	10.31	77	8.50	85	9.32	37	4.08	100	11.00
CL	0–70	0.09	100	9.00	100	9.00	100	9.00	100	9.00	100	9.00	100	9.00
BOD	0—30	0.08	98	7.82	100	8.00	89	7.15	92	7.32	38	3.03	100	8.00
COD	0—30	0.06	99	5.95	100	6.00	98	5.91	92	5.50	33	1.95	100	6.00
TP	0—3	0.07	100	7.00	99	6.94	100	7.00	99	6.95	100	7.00	100	7.00
Boron	0- 0.7	0.05	100	5.00	100	5.00	98	4.89	98	4.92	94	4.70	100	5.00
TSS	0—50	0.02	97	1.94	95	1.89	99	1.98	87	1.74	64	1.29	100	2.00
Fe	0—3.0	0.03	100	3.00	99	2.98	100	3.00	100	3.00	99	2.98	100	3.00
Final Weighted Score		**1.00**	**99.08**		**97.76**		**89.03**		**93.85**		**47.17**		**79.85**	

%: Compilance percentage with the prameters standards

Score: the weithed comilance score

Operational capacity-salinity dynamics at bahr El-Baqar WWTP

Salt load mass balance modeling, based on flow-weighted TDS calculations, assessed operational strategies for Bahr El-Baqar WWTP. The water system of B. El-Baqr WWTP prioritizes collecting high-salinity sources (Shadr Azzam with an average salinity of 3350 mg/L and Om El-Reesh with an average salinity of 2550 mg/L) due to their lack of alternative discharge routes, whereas Bahr El-Baqar drains excess, with an average salinity of 1750 mg/L, can discharge to Manzala Lake; consequently, reduced operational capacity (single-unit operation) mandatorily focuses on high-salinity inflows, while increased capacity enables strategic blending that mitigates influent TDS through proportional incorporation of lower-salinity drainage water. Simulation results demonstrate that reduced operational capacity (fewer units) increases influent TDS (> 2100 mg/L), while full capacity operation enables blending that reduces influent salinity (< 1750 mg/L).

These findinge will be criticale in modeling various scenarios. These findings provide critical insights for scenario formulation in Sect. "Setting alternatives strategies". The framework explicitly accounts for WWTP operational state when calculating system-wide blending ratios, ensuring that simulated scenarios reflect realistic capacity constraints rather than theoretical maxima. This constraint integration prevents the formulation of operationally infeasible strategies, a common deficiency in optimization models that ignore plant-level operational dynamics.

Integrated classification matrix for drainage water sources

Table 7 classifies sources into five operational categories. Class A sources (Faraskur, Lower Serw) exhibit excellent compliance (> 97%) suitable for direct reuse, though limited in volume. Hadous (Class B) offers an optimal balance of quantity and quality with high discharge (56–64 m^3/s) and good compliance (93.85%). El-Matariya (Class C) represents untapped capacity requiring quality enhancement. Bahr El-Baqar WWTP (Class D) delivers reliable volume but requires blending to mitigate salinity. Bahr El-Baqar Drain (Class E) remains unsuitable without extensive pre-treatment.

Setting alternatives strategies

Building on the integrated classification matrix, three operational scenarios were formulated to guide sustainable water allocation for the El-Salam Canal system. These include two proposed strategies based on sustainability thresholds of 75% and 95% (Fig. 5), as well as one Planned Scenario that reflects the formally proposed operational configuration. Each scenario targets a consistent delivery capacity of 93.5 m^3/s at the Sheikh Jaber Canal intake, ensuring alignment with project water demand under varying reliability and seasonal conditions.

- The 75% Scenario represents a moderately conservative strategy, utilizing water quantities available with 75% reliability. This approach maximizes resource availability while accepting a manageable level of hydrological risk. To reflect seasonal variability, this scenario is further disaggregated into summer and winter sub-scenarios, enabling adaptive allocation that accounts for fluctuations in drainage flows and crop water requirements.
- The 95% Scenario adopts a more risk-averse posture, relying only on volumes available with 95% reliability. While this ensures high supply security, the corresponding quantity will be small and may necessitate the use of other low-quality drainage sources. This scenario is particularly relevant for planning in areas

Table 7 Integrated classification matrix for drainage water sources

Source	Quantity metrics			Quality metrics		Operational classification	
	Reliability 75% (m^3/s)	Reliability 95% (m^3/s)	Current reuse	Compliance score (%)	TDS status	Priority class	Recommended strategy
Farskour	13.5—18.0	8.6 – 13.60	53%	99.08	✓ Low	Class A: High Quality	Direct reuse;
Lower Serw	23.8 – 33.9	16.2 – 26.0	66.5%	97.76	✓ Low	Class A: High Quality	Direct reuse; maximize utilization
Hadous Drain	56.0—63.7	38.5- 47.3	57.2%	93.85	✓ Moderate	Class B: High Volume	Direct reuse with monitoring
El-Matariya P.S	21.2 – 28.7	12.3 – 19.9	0%	89.03	⚠ Moderate	Class C: Untapped	Quality enhancement required
B. El-Baqar WWTP	64.80	64.80	21.0%	79.85	✗ High	Class D: Treated	Blending + leaching practices
B. El-Baqar Drain	19.0 – 27.0	15.9 – 24.3	0%	15	✗✗ Very High	Class E: Unsuitable	Extensive pre-treatment required

✓ = Compliant, ⚠ = Moderate concern, ✗ = Non-compliant, ✗✗ = Severe non-compliance

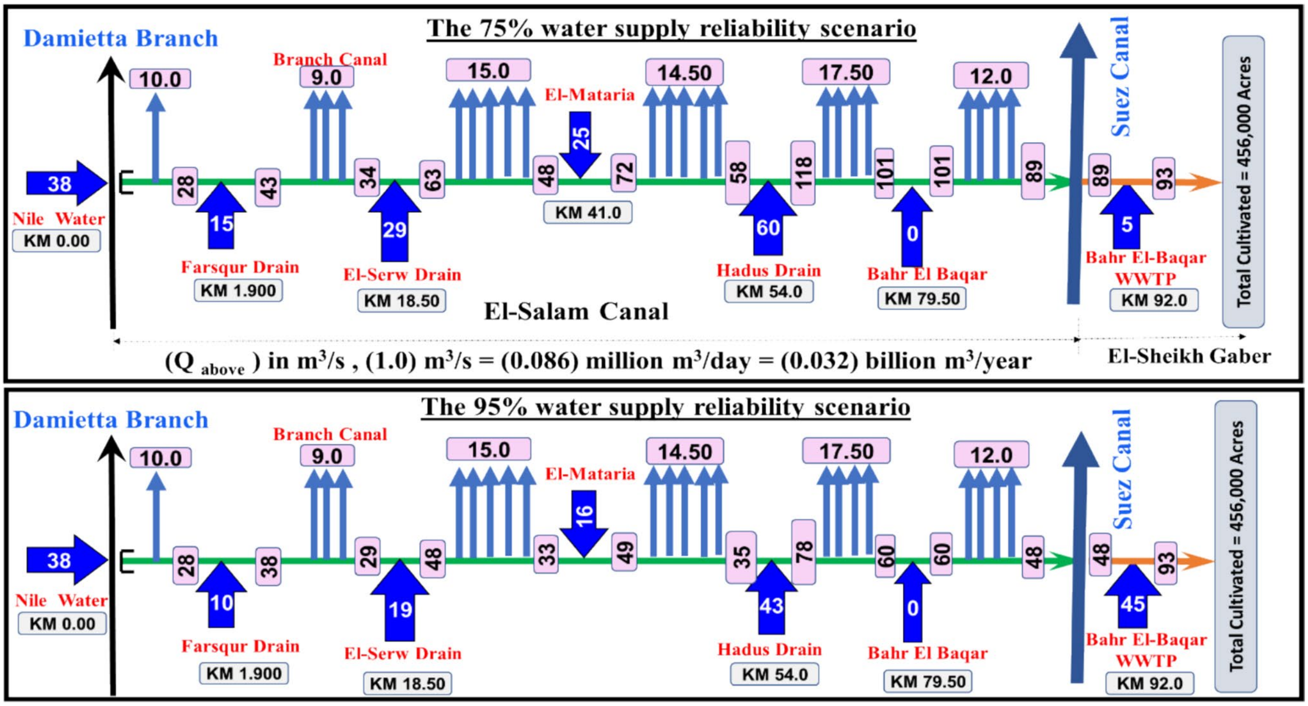

Fig. 5 Alternatives opertional scinario for El-Salam Canal

with drought conditions and high seasonality variation in water availability.

- The Planned Scenario reflects the formally proposed operational plan by the project authorities. It serves as a baseline for comparison, allowing assessment of the added value and feasibility of the proposed sustainability-oriented strategies.

Hydraulic performance assessment of operational scenarios

The calibrated HEC-RAS model evaluated canal hydraulic performance under four operational scenarios; current baseline, planned near-term strategy, and two alternative reliability-based scenarios (75% and 95% thresholds). Hydraulic simulations revealed critical infrastructure constraints under increased flow conditions. The planned scenario induced localized flooding between El-Salam siphon and El-Salam Pumping Station 4 due to elevated Bahr El-Baqar WWTP inflows (64.5 m^3/s) exceeding reach capacity (58 m^3/s). This hydraulic constraint necessitates adjustment of Pumping Station 4 operational curves to increase pumping rates proportionally with upstream inflows, thereby preventing water level exceedance above critical embankment elevations.

Additionally, the 75% and 95% reliability scenarios intensified flood risks, causing embankment overtopping (water levels exceeding crest elevation by 0.3–0.5 m) and bridge submergence at multiple locations. These hydraulic failures demonstrate that existing infrastructure cannot accommodate the increased flows required to meet reliability-based water allocation targets without structural upgrades. Consequently, transitioning from current operations to the 75% and 95% reliability scenarios requires a staged infrastructure upgrades, including selective embankment elevation, siphon capacity enhancement, pumping station improvements, and automated emergency spillway construction.

Taken together, these results indicate that hydraulic capacity constitutes a binding constraint on the feasibility of more reliability-oriented allocation strategies. In other words, even if sufficient quantities and qualities of drainage water are theoretically available, canal infrastructure must be upgraded to convey the additional flows required to realize these gains safely.

Water quality performance under alternative scenarios

The calibrated HEC-RAS water quality model evaluated water quality outcomes under three operational scenarios: planned baseline, 75% annual reliability, and 95% annual reliability. Assessment focused on thrteen parameters critical for agricultural irrigation: SAR, TDS, pH, NO_3,DO,TN, Cl, BOD, COD, TP, Boron, TSS, and Fe.

Table 8 Water quality results and the weighted score for different scenarios

WQPs	Wight	Planned annual		75% annual sustainability		95% annual sustainability		% changes (75% vs. planned)	% changes (95% vs. planned)	% changes (75% vs. 95%)
		value	Score	value	Score	value	Score	value	value	value
SAR	0.2	*7.15*	0.184	5.33	0.134	6.59	− 0.118	− 25.45	− 7.83	− 19.12
TDS	0.21	*1706*	208.32	1134	181.8	1518	101.22	− 33.53	− 11.02	− 25.30
pH	0.08	7.91	0.042	7.98	0.042	7.94	0.0448	0.88	0.38	0.50
NO3	0.11	**3.83**	1.208	8.87	1.224	4.66	1.6874	131.59	21.67	90.34
CL	0.09	69.36	4.248	25.44	4.01	59.04	0.9864	− 63.32	− 14.88	− 56.91
BOD	0.08	15.49	1.3	13.8	1.29	14.75	1.22	− 10.91	− 4.78	− 6.44
COD	0.06	33.12	0.287	35.27	0.284	33.86	0.3684	6.49	2.23	4.16
TP	0.07	0.39	0.155	0.76	0.157	0.53	0.1729	94.87	35.90	43.40
Boron	0.05	0.075	0.032	0.063	0.032	0.072	0.0314	− 16.45	− 4.51	− 12.50
TSS	0.02	26.77	0.43	28.17	0.44	27.06	0.4588	5.23	1.08	4.10
Fe	0.03	0.271	0.087	0.106	0.087	0.216	0.0835	− 60.89	− 20.30	− 50.93
Weighted score	1	–	65.70	–	189.6	–	106.2	75%—planned 123.90	95%—planned 40.50	75%—95% 83.40

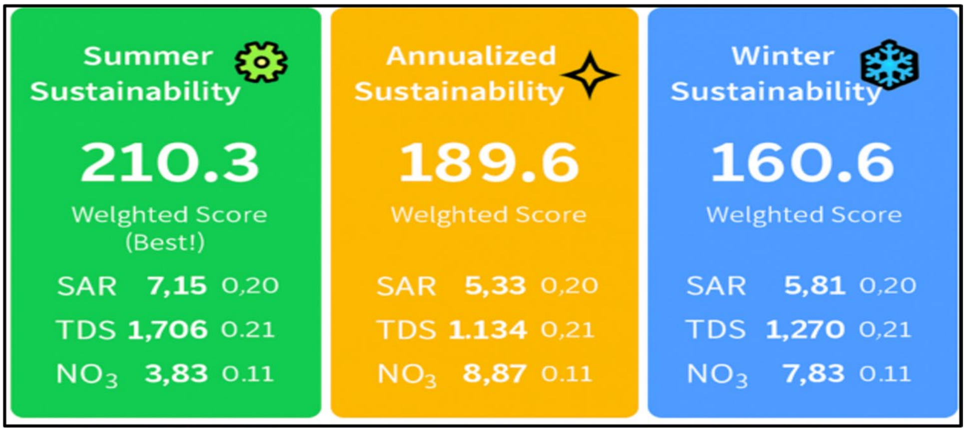

Fig. 6 Seasonal variation in weighted water quality scores under the 75% scenario

Comparative water quality performance

Results (Table 8) demonstrate substantial improvements under reliability-based scenarios compared to the planned baseline. The 75% scenario achieved significant reductions in salinity and highly weighted parameters: SAR decreased by 25.5% (5.33 vs. 7.15) and TDS by 33.5% (1134 vs. 1706 mg/L), enhancing soil permeability and reducing sodicity risks. The 95% scenario exhibited intermediate performance (SAR: 6.59, TDS: 1,518 mg/L), representing 19.1% and 25.3% reductions, respectively.

The weighted analysis highlights clear differences among scenarios as the planned baseline scored 65.7 points, while the 75% scenario achieved 189.6 points (+188.4%), a net gain of 123.9 points that far exceeds normal operational variability and confirms substantial water quality improvement. The 95% scenario reached 106.2 points (+61.5%), showing meaningful progress though less pronounced. Overall, the 75% scenario offers the strongest balance of feasibility and quality gains, while the 95% scenario provides a secure, reliability-focused alternative that still outperforms the baseline. Performance hierarchies directly reflect source water selection strategies. The 75% scenario prioritizes maximum allocation from the four highest-quality sources, ensuring superior water quality. The 95% scenario distributes allocations across broader but lower-ranked sources, yielding intermediate performance. The planned scenario's heavy reliance on Bahr El-Baqar (elevated salinity and SAR) fundamentally limits water quality achievement.

The planned vs. reliability scenarios show water quality depends mainly on source selection, not system limits. By prioritizing high-quality drains, the 75% scenario reduces SAR and TDS substantially, moving El-Salam Canal to safer salinity levels for Delta soils. This explains the large quality gains from simple allocation changes.

Seasonal performance variability

The 75% scenario exhibited pronounced seasonal differentiation (Fig. 6): summer operations achieved optimal water quality (weighted score: 216.3 points, + 14.1% above annual average) through maximum utilization of high-quality sources (Faraskur, El-Serw, Hadous, El-Matariya), yielding superior SAR (5.08) and TDS (1008 mg/L). Winter performance (score: 160.6) reflected increased reliance on the lower-quality Bahr El-Baqar treatment plant to meet demand, resulting in elevated salinity (TDS: 1270 mg/L) and SAR (5.81). Despite this seasonal variation, winter water quality substantially exceeds planned baseline performance year-round.

Agricultural sustainability implications

The reliability-based scenarios substantially reduce crop yield losses and soil degradation risks. The 75% scenario achieved a 188% improvement in weighted score, driven by substantial reductions in SAR and TDS, which enhance soil hydraulic conductivity, expand crop tolerance margins, and reduce leaching requirements. Seasonal performance further suggests adaptive crop calendars, with summer periods offering exceptional water quality (score: 216.3) suitable for salt-sensitive, high-value crops. The 95% scenario, though more conservative, still provided a 61.5% gain, confirming that any transition toward reliability-based allocation yields meaningful improvements. Moderate increases in nutrient parameters (NO_3, TP) remained within regulatory limits, underscoring that the dominant reductions in SAR and TDS provide strong justification for adopting sustainability-oriented management frameworks.

Soil salinity dynamics and leaching requirements under water quality scenarios

Scenario performance analysis

SWAP modeling revealed water quality's direct impact on soil salinity and leaching (Table 9).

Baseline Performance (Planned Scenario): Using drainage water (EC: 2.8 dS/m) resulted in critical root zone salinity (ECe: 7.17 ± 0.23 dS/m), requiring the highest leaching fraction (LR = 15.5%). Given actual field irrigation rates of 23.80 m^3/feddan/day, this translated to 3.69 m^3/feddan/day allocated solely for leaching purposes, representing a substantial operational water demand. Soil salinity levels exceeded tolerance thresholds for wheat (6.0 dS/m) and maize (4.0 dS/m), posing immediate yield risks and long-term soil degradation concerns.

95% water supply reliability scenario: A modest water quality improvement (EC: 2.37 dS/m) resulted in a reduction of soil salinity to 6.71 ± 0.19 dS/m, a marginal 6.4% reduction. Leaching requirements remained high at 13.6%, offering limited operational benefits with only a 1.90% decrease in LR, equalling 0.45 m^3/feddan/day savings.

75% Summer- water supply reliability scenario): Strategic seasonal allocation high-quality water during summer (EC: 1.57 dS/m) and moderate quality in winter (EC: 3.65 dS/m), achieved optimal performance. Summer soil salinity reached 3.65 ± 0.12 dS/m (49.1% reduction; $P < 0.001$), requiring only 8.5% leaching fraction (2.04 m^3/feddan/day). This saved 1.68 m^3/feddan/day in summer, translating to 610.0 m^3/feddan/year savings (13.5%), while maintaining ECe below critical crop tolerance thresholds year-round.

Systematic comparison revealed distinct performance thresholds among scenarios. The 95% scenario (EC: 2.37 dS/m) achieved only marginal improvement over baseline (6.4% salinity reduction, $P = 0.089$; 0.45 m^3/feddan/day savings), indicating that drainage water EC is recommended to decrease below 2.0 dS/m to generate meaningful benefits. The 75% winter scenario (EC: 1.98 dS/m) significantly reduced soil salinity to 5.05 ± 0.15 dS/m (29.6% reduction; $P < 0.01$) and saved 1.02 m^3/feddan/day (370.0 m^3/feddan/year). However, the 75% summer-optimized scenario demonstrated superior performance by strategically allocating high-quality water during the critical maize season, achieving 3.65 ± 0.12 dS/m soil salinity (49.1% reduction; $P < 0.001$) and 1.68 m^3/feddan/day savings (610.0 m^3/feddan/year), 64.7% greater than the winter scenario.

The linear ECe-irrigation EC relationship ($R^2 = 0.95$, 2.5 × concentration factor) confirms $EC < 2.0$ dS/m is required for meaningful benefits. Seasonal optimization substantially outperforms uniform allocation while maintaining crop-safe salinity levels. These findings empirically support one of the core hypotheses of the framework: that seasonally targeted use of higher-quality drainage water can achieve larger and more durable soil salinity reductions than uniform, annual average-based allocations, for the same or even lower total water input. This nuance is frequently overlooked in classical leaching requirement calculations that assume stationary water quality.

Table 9 Impact of irrigation water quality on soil salinity, leaching requirements, and operational water savings

Scenario	Water EC (dS/m)	Soil Ec (dS/m)	Leaching (%)	Daily leaching (m3/feddan/day)	Savings vs. planned (m3/feddan/year)
Planned	2.80	7.17	15.50	3.69	Baseline
95% Annual	2.37	6.71	13.60	3.24	165.50
75% Winter	1.98	5.05	11.25	2.67	370.0
75% Summer	1.57	3.65	8.50	2.02	610.0

Table 10 Multi-dimensional integrated performance comparison matrix

Dimension	Performance indicator	Planned (baseline)	95% sustainability	75% winter	75% annual	75% summer	Best scenario
Water quality	Final quality score	Baseline	+40.43	+94.92	+123.84	+150.58	75% Summer
	Irrigation water EC (dS/m)	2.80	2.37	1.98	1.75	1.57	75% Summer
Soil salinity	Root zone ECe (dS/m)	7.17 ± 0.23	6.71 ± 0.19	5.05 ± 0.15	4.37 ± 0.14	3.65 ± 0.12	75% Summer
	Δ ECe vs. Baseline (dS/m)	Reference	− 0.46 (6.4%)	− 2.12 (29.6%)	− 2.80 (39.1%)	− 3.52 (49.1%)	75% Summer
	FAO threshold status	Critical (> 6.0)	Critical (> 6.0)	Moderate (5–6)	Acceptable (< 4.5)	Safe (< 4.0)	75% Summer
Leaching management	Leaching requirement (%)	15.50	13.60	11.25	9.70	8.50	75% Summer
	Daily leaching (m^3/fed/day)	3.69	3.24	2.68	2.31	2.02	75% Summer
	Δ LR vs. baseline (%)	Reference	− 1.90 (12.3%)	− 4.25 (27.4%)	− 5.80 (37.4%)	− 7.00 (45.2%)	75% Summer
Water savings	Annual savings (m^3/fed/year)	Baseline	167.90	370.0	503.70	610.0	75% Summer
	% of Total irrigation	Baseline	3.7%	8.2%	11.1%	13.5%	75% Summer
Agronomic impact	Wheat yield loss (%)	8.3%	7.0%	2.5%	< 1.0%	< 1.0%	75% Summer
	Maize yield loss (%)	38.9%	35.2%	18.6%	9.4%	4.7%	75% Summer
Overall performance	Sustainability classification	Unsustainable	Marginal	Substantial	High impact	Optimal	75% Summer

Negative Δ values indicate improvements (reductions) in soil salinity and leaching requirements

Water Savings calculated based on irrigation rate of 23.80 m^3/feddan/day

Agronomic and soil health implications

Cenario salinity variations directly impact crop productivity. Baseline conditions (ECe: 7.17 dS/m) exceed tolerance thresholds, causing (8–12% wheat) and (35–40% maize) yield losses (Qadir et al. 2014). In contrast, the 75% summer scenario maintained salinity at 3.65 dS/m, limiting yield losses to < 5% for both crops (Deepasree & Shivananda 2024).

Beyond immediate yield impacts, salinity levels > 6 dS/m accelerate long-term soil degradation through clay dispersion, aggregate breakdown, and reduced biological activity, necessitating higher fertilizer inputs (Qadir et al. 2014). By maintaining ECe below 4.4 dS/m, the 75% sustainability scenario mitigates these risks, ensuring both soil health and water-use efficiency.

These results establish a clear cause effect relationship: improved drainage water quality significantly reduces soil salinity, lowers leaching requirements, and generates substantial water savings. The 75% summer-optimized scenario emerges as the most effective management strategy, delivering dual benefits of enhanced soil sustainability and reduced operational water demand.

Integrated performance matrix

Following comprehensive evaluation of water quality, soil salinity, leaching requirements, and operational implications, a multi-dimensional comparative matrix was constructed to synthesize scenario performance across technical, and agronomic dimensions (Table 10). The 75% summer sustainability scenario demonstrated optimal overall performance, achieving maximum water savings (610.0 m^3/feddan/year) and soil salinity control while requiring moderate infrastructure investment. The planned baseline exhibited the poorest performance across all dimensions, highest soil salinity (7.17 dS/m), maximum leaching demand (15.5%), severe yield losses (8–39%), and minimal infrastructure, representing an unsustainable trajectory. The 95% sustainability scenario provided marginal improvements (+ 40.43 quality score; 167.90 m^3/feddan/year savings) insufficient to justify the required infrastructure costs, while the 75% annual and winter scenarios offered intermediate performance with substantial benefits.

The magnitude of improvements in the 75% scenarios, soil salinity reductions of 2.12–3.52 dS/m and leaching fraction reductions of 4.25–7.00%, substantially exceeded typical SWAP model uncertainty (± 0.3 dS/m for ECe; ± 1.5% for LR), confirming robust and agronomically significant benefits. Critically, all 75% scenarios reduced root zone salinity below or near the FAO threshold of 4.0 dS/m for salt-sensitive crops, compared to 7.17 dS/m under baseline conditions. This threshold crossing translates to substantial yield protection, preventing approximately 35–40% maize productivity losses and 8–12% wheat losses projected under baseline salinity levels.

From a policy perspective, the comparison in Table 9 demonstrates that sustainability-oriented allocation does not necessarily require additional freshwater, but rather a smarter deployment of existing drainage resources within hydraulic and reliability constraints. The fact that the 75% summer scenario simultaneously improves water quality, reduces soil salinity, and saves water suggests that re-optimizing current operations can generate no-regret gains, providing a compelling argument for piloting such strategies in the El-Salam system and similar DWR schemes.

Conclusion and recomendation

This study developed an integrated multi-model framework combining HEC-RAS, SWAP, and multi-criteria decision analysis to optimize drainage water reuse for 620,000 feddan served by Egypt's El-Salam Canal. Three water supply reliability scenarios were evaluated: planned baseline, 95% reliability, and 75% reliability with seasonal variability.

Key findings (prioritized by impact magnitude)

This study demonstrates that strategic drainage water source selection can simultaneously address soil salinity, crop productivity, and water conservation challenges in large-scale agricultural reuse systems. Four primary findings emerged:

- *Primary Finding -Soil Salinity and Crop Productivity Preservation (Highest Impact)*: The 75% reliability scenario reduced root zone salinity by 49.1% (ECe: 3.65 ± 0.12 dS/m vs. 7.17 ± 0.23 dS/m planned), preventing wheat/maize yield losses > 30%. The relationship between irrigation water EC and soil salinity followed a linear function ($ECe = 2.51 \times EC + 0.14$; $R^2 = 0.97$), indicating a 2.5 × concentration factor that amplifies water quality impacts under semi-arid conditions.
- *Secondary Finding—Seasonal Water Quality Optimization (Operational Innovation)*: Strategic seasonal allocation outperformed uniform year-round approaches by 35–65% in water quality scoring. Summer optimization (utilizing El-Serw, Farskor, Hadous, El-Matria sources) peaked at 216.30 quality points (+ 14.1% above annual average). Winter operation (160.64 points) accommodated increased reliance on Bahr El-Baqar treated effluent, accepting moderate quality degradation during periods of lower crop sensitivity. This temporal optimization maximized limited high-quality drainage resources while maintaining operational feasibility across all irrigation seasons.
- *Tertiary Finding—Water Quality Enhancement (Source Selection Impact)*: Drainage water source—selection achieved 25–63% reductions in key parameters (SAR, TDS, chloride), increasing integrated quality scores by 188% (75% scenario) vs. only 62% (95% scenario), establishing optimal cost–benefit balance.
- *Tertiary Finding—Substantial water conservation potential (Resource Efficiency)*: Strategic source selection under the 75% reliability scenario reduced leaching requirements from 15.5% to 8.5% of irrigation water, savings about 610 m^3/feddan/year.

These prioritized findings demonstrate that sustainability-oriented drainage water management simultaneously enhances water quality, preserves soil health, sustains crop productivity, and achieves water conservation objectives.

Policy implications and operational recommendations

The officially planned scenario, relying heavily on Bahr El-Baqar Wastewater Treatment Plant without strategic source differentiation, poses significant risks: elevated soil salinity (ECe: 7.17 dS/m), intensive leaching demands (15.5%), and severe yield reductions (8–40%). Continued implementation would accelerate soil degradation, reduce crop productivity, and necessitate higher freshwater quantities for salt mitigation, directly contradicting national water sustainability objectives.

In contrast, the 75% reliability scenario, particularly with summer optimization, enhances water availability, preserves soil health, and maintains productivity through strategic drainage source selection. Achieving 49% soil salinity reduction, 10–14% irrigation water conservation, and sustaining yields within 5% of optimal levels demonstrates that sustainability and productivity are complementary rather than competing objectives when management is scientifically informed. These findings directly advance Sustainable Development Goals 2 (Zero Hunger) and 6 (Clean Water and Sanitation) by maintaining agricultural productivity, improving water use efficiency, and enhancing climate resilience through reduced soil degradation and decreased freshwater dependence.

To enhance the performance of drainage water reuse projects, three strategic measures are strongly recommended. First, operational efficiency should be improved by implementing seasonal source allocation, prioritizing high-quality drains during sensitive crop periods and applying appropriately robust threshold scenarios for reliability. Second, a comprehensive monitoring framework needs to be established, including continuous water quality surveillance and quarterly soil salinity assessments at multiple depths (0–40 cm, 80–120 cm), fully integrated with adaptive management protocols. Third, sustainability assurance should be achieved through annual multi-dimensional performance evaluations encompassing water quality, soil salinity trends, crop productivity, irrigation efficiency, and groundwater dynamics. This integrated approach fosters early intervention before potential degradation becomes irreversible, thereby ensuring the long-term viability and resilience of agricultural systems.

Scientific contributions and novelty validation

This research advances drainage water reuse management through three key innovations that address limitations identified in recent modeling and optimization studies. **First,** this study introduces a staged-integration framework that advances beyond separate tools or parallel coupling approaches (Butcher & Wool 2021; Lawal et al. 2023; Helal et al. 2021; Karamouz & Mohammadpour 2017; Shah et al. 2024), which address each of the drainage water reuse concerns independently and reconcile conflicts only post-optimization. The proposed decision-cascade architecture delivers a single, operationally coherent blending strategy that simultaneously satisfies water availability, regulatory compliance, hydraulic capacity, and agronomic sustainability. This is demonstrated through the 75% reliability scenario for El-Salam Canal, which proves hydrologically feasible, hydraulically validated, water-quality compliant, and agronomically sustainable.

Second, while recent drainage water reuse studies have relied on static or annually averaged salinity thresholds (Minhas et al. 2020), this study demonstrates that seasonal water quality allocation aligned with crop-specific sensitivity during critical growth stages, substantially enhances system performance. The 75% reliability scenario achieved 35–65% improvement over uniform year-round blending, with summer optimization (El-Serw/Farskor/Hadous/El-Matria sources) delivering 216.30 quality points versus winter's 160.64 points. This establishes temporal matching of water quality to crop demand as a core design principle, addressing a critical gap in optimization frameworks that overlook intra-seasonal tolerance dynamics.

Third, while the reliability-performance trade-off has been discussed conceptually in water resources planning (Mcclymont et al. 2020), it has not been quantitatively integrated with water quality in drainage reuse systems. This study explicitly quantifies the reliability-quality trade-off, showing the 95% reliability scenario achieves only 61.5% quality improvement (106.15 points) versus 188.4% (189.56 points) for the 75% scenario. Maximizing supply reliability forces dependence on poorer sources (Bahr El-Baqar), while moderate 75% reliability enables strategic selection of high-quality sources (El-Serw/Farskor), delivering superior overall performance. This risk-informed assessment establishes 75% as the optimal reliability threshold for DWR systems, providing actionable guidance for balancing supply security and water quality objectives.

Study limitations and testable directions for future research

This study has several limitations that define clear, testable directions for future research. First, the reliance on a five-year monitoring period with monthly water-quality data may not fully capture short-term variability in drainage sources. Future research should test whether higher-frequency monitoring improves blending optimization performance by integrating remote sensing and drone-based observations with in-situ measurements and comparing optimization robustness under monthly versus sub-monthly data inputs. Second, socio-economic and institutional factors were not explicitly incorporated. A testable hypothesis is that embedding stakeholder preferences and policy constraints within the optimization framework alters optimal blending strategies and reliability targets. This can be evaluated by coupling the model with multi-criteria decision analysis and participatory decision-support tools.

Third, the absence of groundwater–surface water interaction modeling limits long-term impact assessment. Future studies should test whether coupling the framework with groundwater flow and salinity transport models (e.g., SWAT-based systems) significantly affects optimal reuse allocations and sustainability thresholds under multi-decadal scenarios. Finally, crop responses were represented using generalized salinity limits. Future research should test whether integrating crop and growth-stage-specific salinity tolerance functions improves yield prediction accuracy, through comparison with field-observed yield responses under dynamic salinity conditions.

Concluding statement

This study demonstrates that scientifically informed, sustainability-oriented drainage water management can simultaneously address water scarcity, soil health, and agricultural productivity in arid and semi-arid regions. The integrated multi-model framework provides a replicable methodology for optimizing marginal water resources, directly supporting Egypt's National Water Resources Plan 2037 and offering a practical template for water-stressed agricultural systems globally. Strategic implementation of the 75% reliability scenario with seasonal optimization represents a transformative pathway from unsustainable baseline practices toward resilient, productive, and environmentally responsible agricultural water management.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

Abdel-Azim R, Allam MN (2005). Agricultural drainage water reuse in Egypt: strategic issues and mitigation measures. Non-conventional water use: WASAMED project, 117: 105–117. http://resources.ciheam.org/om/pdf/b53/00800755.pdf.

Abou Jaoude G, Mumm O, Carlow VM (2022) An overview of scenario approaches: a guide for urban design and planning. J Plann Lit 37(3):467–487. https://doi.org/10.1177/08854122221083546

Agrama AA, Amer AS (2012) Investigation of El-Salam canal water quality, south El-Qantara sharq area. J Appl Sci Res 8(4):1927–1935

Almanaseer N, Hindiyeh M, Al-assaf R (2020) Hydrological and environmental impact of wastewater treatment and reuse on Zarqa River Basin in Jordan. Environments 7(2):14

Ashour E, Zeidan B, Elshemy M (2021) Assessment of agricultural drainage water reuse for irrigation in El-Behira Governorate, Egypt. Water Sci 35(1):135–153. https://doi.org/10.1080/23570008.2021.1982336

Barnes J (2014) Mixing waters: the reuse of agricultural drainage water in Egypt. Geoforum 57:181–191. https://doi.org/10.1016/j.geoforum.2012.11.019

Butcher J, Wool TA (2021) A coupled hydrodynamic (HEC-RAS 2D) and water quality model (WASP) for simulating flood-induced soil, sediment, and contaminant transport. J Flood Risk Manag 14(4):e12747. https://doi.org/10.1111/jfr3.12747

Buthelezi S, Mutanga O, Sibanda M, Odindi J, Clulow AD, Chimonyo VGP, Mabhaudhi T (2023). Assessing the prospects of remote sensing maize leaf area index using UAV-derived multi-spectral data in smallholder farms across the growing season.

Cheng S, Meng F, Wang Y, Zhang J, Zhang L (2024) The potential linkage between sediment oxygen demand and microbes and its contribution to the dissolved oxygen depletion in the Gan River. Front Microbiol 15(July):1–16. https://doi.org/10.3389/fmicb.2024.1413447

Christodoulou SE (2011) Water network assessment and reliability analysis by use of survival analysis. Water Resour Manage. https://doi.org/10.1007/s11269-010-9679-8

Deepasree A, Shivananda TL (2024) Enhancing crop saline stress tolerance and soil remediation with phytobeneficial bacteria: diverse approaches for improvement. Asian J Soil Sci Plant Nutr 10(2):539–558

Dudley LM, Ben-Gal A, Shani U (2008) Influence of plant, soil, and water on the leaching fraction. Vadose Zone J 7(2):420–425. https://doi.org/10.2136/vzj2007.0103

Dudley LM, State F (2008). Drainage water reuse : biological , physical , and technological considerations for system management. pp. 25–35. https://doi.org/10.2134/jeq2007.0314.

El Gamal F, Mostafa H, Shalby A, Guelloubi R (2005) Reuse of low quality water in Egypt. Ciheam/eu DG Res 53:93–103

El-Sayed A, Shaban M (2019) Developing Egyptian water quality index for drainage water reuse in agriculture. Water Environ Res 91(5):428–440. https://doi.org/10.1002/wer.1038

FAO (2021) World Food and Agriculture - Statistical Yearbook 2021. Rome https://doi.org/10.4060/cb4477en

Ferrans P, Torres MN, Temprano J, Pablo J, Sánchez R (2022) Science of the total environment sustainable urban drainage system (SUDS) modeling supporting decision-making: a systematic quantitative review. Sci Total Environ 806:150447

Franciosi C, Di Pasquale V, Iannone R, Miranda S (2020) Multi-stakeholder perspectives on indicators for sustainable maintenance performance in production contexts: an exploratory study. J Qual Maint Eng 27(2):308–330. https://doi.org/10.1108/JQME-03-2019-0033

Genuchten Van M. Th. (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Gichamo T, Gökçekuş H, Uzun D, Gelete G (2020) Evaluation of different natural wastewater treatment alternatives by fuzzy PROMETHEE method. Desalin Water Treat 177:400–407. https://doi.org/10.5004/dwt.2020.25049

Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. Water Resour Manage. https://doi.org/10.1007/s11269-006-9112-5

Harmel RD, Preisendanz HE, King KW, Busch D, Birgand F, Sahoo D (2023) A review of data quality and cost considerations for water quality monitoring at the field scale and in small watersheds. Water (Switzerland) 15(17):1–19. https://doi.org/10.3390/w15173110

Heidarigharehsoo N, Saidi S (2023) Exploring alternative bus operations strategies for adaptive and efficient transit systems in the face of disruptions. J Public Transp. https://doi.org/10.1016/j.jpubtr.2023.100060

Helal E, Shaban M, Abd El-Karim E, Ellayen A (2021) A comprehensive management model to maximize the benefits of agriculture drainage water reuse. Water Environ Res 93(9):1722–1733. https://doi.org/10.1002/wer.1559

Helmecke M, Fries E, Schulte C (2020) Regulating water reuse for agricultural irrigation: risks related to organic micro-contaminants. Environ Sci Eur. https://doi.org/10.1186/s12302-019-0283-0

Huang X, Zhao Y, Guo T, Mao X (2024) Enhancing SWAP simulation accuracy via assimilation of leaf area index and soil moisture under different irrigation, film mulching and maize varieties conditions. Comput Electron Agric 218:10862. https://doi.org/10.1016/j.compag.2024.108625

Ibrahim MM, Shaban M, El-karim EA, Samy A (2025) Multi-criteria data-driven framework for drainage water reuse sustainability. Ain Shams Eng J 16(12):103782. https://doi.org/10.1016/j.asej.2025.103782

Jiang J, Feng S, Huo Z, Zhao Z, Jia B (2011) Application of the SWAP model to simulate water-salt transport under deficit irrigation with saline water. Math Comput Model 54(3–4):902–911. https://doi.org/10.1016/j.mcm.2010.11.014

Jo CD, Choi SY, Kwon HG (2024) Statistical analysis of water quality change by total maximum daily load policy stage. Appl Water Sci 14(8):1–14. https://doi.org/10.1007/s13201-024-02239-7

Karamouz M, Mohammadpour P (2017) Assessment of sustainability in water supply-demand considering uncertainties. Water Resour Manage. https://doi.org/10.1007/s11269-017-1703-9

Karim MR, Syeed MMM, Rahman A, Ayaz Rabbani K, Fatema K, Khan RH, Hossain MS, Uddin MF (2025) A comprehensive dataset of surface water quality spanning 1940–2023 for empirical and ML adopted research. Sci Data 12(1):1–13. https://doi.org/10.1038/s41597-025-04715-4

Lawal IM, Bertram D, White CJ, Jagaba AH (2023) Integrated framework for hydrologic modelling in data-sparse watersheds and climate change impact on projected green and blue water sustainability. Front Environ Sci. https://doi.org/10.3389/fenvs.2023.1233216

Leenaars JGB, Claessens L, Heuvelink GBM, Hengl T, González MR, Bussel LGJV, Guilpart N, Cassman KG, Leenaars JGB, Claessens L, Heuvelink GBM, Hengl T, González MR (2023) Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa to cite this version: HAL Id: hal-03938215. Geoderma 324:18–36. https://doi.org/10.1016/j.geoderma.2018.02.046

Li X, Zhang C, Huo Z, Adeloye AJ (2020) A sustainable irrigation water management framework coupling water-salt processes simulation and uncertain optimization in an arid area. Agric Water Manage 231(17):105994

Lian H, Sun Z, Xu C, Gu F (2022) The relationship between the distribution of water and salt elements in arid irrigation areas and soil salination evolution. Front Earth Sci 10(April):1–14. https://doi.org/10.3389/feart.2022.852485

López-gunn E, Rica M, Zugasti I, Hernaez O, Pulido-velazquez M (2024) Use of the Delphi method to assess the potential role of enhanced information systems in Mediterranean groundwater management and governance. Water Policy 26(12):1183–1206. https://doi.org/10.2166/wp.2024.033

Łuczak K, Czerniawska-Kusza I, Rosik-Dulewska C, Kusza G (2021) Effect of NaCl road salt on the ionic composition of soils and *Aesculus hippocastanum* L. foliage and leaf damage intensity. Sci Rep 11(1):1–10. https://doi.org/10.1038/s41598-021-84541-x

Machado RMA, Serralheiro RP (2017) Soil salinity: effect on vegetable crop growth. Management practices to prevent and mitigate soil salinization. Horticulturae. https://doi.org/10.3390/horticulturae3020030

Mateo-Sagasta J, (IWMI), Al-Hamdi M, (FAO), AbuZeid K, (AWC), Funded. (2023). Water reuse in the middle East and North Africa. In: Water reuse in the middle East and North Africa: a sourcebook. In Arabic. https://doi.org/10.5337/2023.221

Mcclymont K, Gasparini D, Cunha F, Maidment C, Ashagre B, Floriano A, Batalini M, Macedo D, N MF, Marcus N, Rajendran L, Imani M (2020) Towards urban resilience through sustainable drainage systems: a multi-objective optimisation problem. J Environ Manage. https://doi.org/10.1016/j.jenvman.2020.111173

Minhas PS, Ramos TB, Ben-gal A, Pereira LS (2020) Coping with salinity in irrigated agriculture : crop evapotranspiration and water management issues. Agric Water Manage 227:105832. https://doi.org/10.1016/j.agwat.2019.105832

Mishra AK, Das R, George Kerry R, Biswal B, Sinha T, Sharma S, Arora P, Kumar M (2023) Promising management strategies to improve crop sustainability and to amend soil salinity. Front Environ Sci. https://doi.org/10.3389/fenvs.2022.962581

Nabayi A, Santuraki HA, Girei AH, Hayatu NG, Haruna FD, Yusif SA, Lukman SA (2020) Soil structure indices under different tillage systems of sandy loam soil in Hadejia, Jigawa state, Nigeria. Agric Sci Technol 12(1):71–76. https://doi.org/10.15547/ast.2020.01.013

Okuda Y, Onishi J, Shirokova YI, Kitagawa I, Kitamura Y (2020). Water and salt balance in agricultural lands under leaching with shallow subsurface drainage used in combination with cut-drains. Water (Switzerland), Vol. 15.

Qadir M, Quillérou E, Nangia V, Murtaza G, Singh M, Thomas RJ, Drechsel P, Noble AD (2014) Economics of salt-induced land degradation and restoration. Nat Resour Forum 38:282–295. https://doi.org/10.1111/1477-8947.12054

Qureshi AS, Perry C (2021). Managing water and salt for sustainable agriculture in the indus basin of Pakistan. pp. 1–14.

Radcliffe JC, Page D (2020) Water reuse and recycling in Australia — history, current situation and future perspectives. Water Cycle 1:19–40. https://doi.org/10.1016/j.watcyc.2020.05.005

Raslan AM, Riad PH, Hagras MA (2020) 1D hydraulic modelling of Bahr El-Baqar new channel for northwest Sinai reclamation project, Egypt. Ain Shams Eng J 11(4):971–982. https://doi.org/10.1016/j.asej.2020.02.005

Sanad H, Lhaj MO, Zouahri A, Saafadi L, Dakak H, Mouhir L (2024) Groundwater pollution by nitrate and salinization in Morocco: a comprehensive review. J Water Health 22(10):1756–1773. https://doi.org/10.2166/wh.2024.024

Warrick AW, Lomen DO, Islas A (1990) An analytical solution to Richards' equation for a draining soil profile. Water Resour Res 26(2):253-258. https://doi.org/10.1029/WR026i002p00253

Sediyama JAS, Alassane D, da Silva RHT, Ribeiro Júnior JI (2023) Consistencies of the capability indices based on the normal probability distribution. Gestão Produção 30:1–15. https://doi.org/10.1590/1806-9649-2022V29E5722

Shaban M (2014) Drainage water reuse: state of control and process capability evaluation. Water Air Soil Pollut. https://doi.org/10.1007/s11270-014-2168-6

Shaban M, El-sayed EA (2012) Regression based modeling and numerical simulations for the assessment of water management practices for El-Salam Canal project, Egypt. Nile Basin Water Sci Eng J 5(1):32

Shah W, Chen J, Ullah I, Shah M, Ullah I (2024) Application of RNN-LSTM in Predicting Drought Patterns in Pakistan: A Pathway to Sustainable Water Resource Management. Water. https://doi.org/10.3390/w16111492

Sharma V, Changade N, Madane D, Yadav K, Tarate S (2024) Development of growth-stage specific crop coefficient for drip irrigated wheat crop grown in climatic conditions of Jalandhar, Punjab. J Agrometeorol. https://doi.org/10.54386/jam.v26i3.2628

Steppuhn H, Grieve CM (2004) Root-zone salinity. Crop Sci 45(1):209. https://doi.org/10.2135/cropsci2005.0209

Tosic M, Narváez-Flórez S, Parra J (2013) Selection of parameters in the design of beach coastal water quality monitoring programs. 8:43-51. https://doi.org/10.21676/23897864.731

Wang X, Zhang J, Babovic V, Gin KYH (2019) Environmental modelling & software a comprehensive integrated catchment-scale monitoring and modelling approach for facilitating management of water quality. Environ Model Softw 120(July):104489. https://doi.org/10.1016/j.envsoft.2019.07.014

Whalley WR, Hawkesford MJ, Ashton RW, Atkinson B, Atkinson JA, Sturrock CJ, Bennett MJ, Mooney SJ (2021) The interaction between wheat roots and soil pores in structured field soil. J Exp Bot 72(2):747–756. https://doi.org/10.1093/jxb/eraa475

Wurtsbaugh WA, Paerl HW, Dodds WK (2019) Nutrients, eutrophication and harmful algal blooms along the freshwater to marine continuum. Wires Water 6(5):1–27. https://doi.org/10.1002/WAT2.1373

Yin W, Yang X, Liu W (2025) Sustainable management and regulation of agricultural water resources in the context of global climate change. Sustainability (Switzerland) 17(6):1–5. https://doi.org/10.3390/su17062760

Zainal NN, Talib SHA (2024) Review paper on applications of the HEC-RAS model for flooding, agriculture, and water quality simulation. Water Pract Technol 19(7):2883–2900. https://doi.org/10.2166/wpt.2024.173