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Optimized Operational Strategies for Managing Salinity in Reused Drainage Water

Mohammad Mahmoud Ibrahim [1], Mohamed Shaban Mohamed AbuSalama [2], Ehab Abd El-karim Roshdy [2,*] , Abeer Samy [1]

[1] Civil Engineering Department, Faculty of Engineering at Shoubra, Benha University, Cairo, Egypt.
[2] Drainage Research Institute, National Water Research Centre, Cairo, Egypt.
**Corresponding author*

E-mail address: mohamed.ibrahim@feng.bu.edu.eg, salamashaban@gmx.com, engineerehababdelkreem@gmail.com, abeer.samy@feng.bu.edu.eg

Abstract: Drainage Water Reuse (DWR) is vital for irrigation in arid regions; however, salinity remains a major limit on crop yields and long-term soil health. This study tests three operating strategies for the Bahr El-Baqar Wastewater Treatment Plant (WWTP), which mixes differently saline drains and discharges into El-Salam Canal, itself blending Nile water with agricultural drainage. The strategies seek to improve canal salinity while balancing treatment capacity, operating costs, and agronomic needs. A calibrated hydro-salinity mixing model simulated three strategies, using seasonal 95th-percentile flows and TDS to represent conservative winter and summer conditions. In Strategy 1, the WWTP is operated progressively from a single unit (0.8 MCM/d) up to full capacity (5.21 MCM/d) while retaining high-salinity drains in the influent; despite the 6.5-fold increase in discharge, canal TDS remains 60–81% above the baseline (875 mg/L), stabilizing at 1431–1585 mg/L and effectively limiting cultivation to salt-tolerant crops. Strategy 2 replaces these drains with moderate-salinity sources, enabling operation at the design capacity of 5.6 MCM/d while keeping the Total Dissolved Solids (TDS) within 1039 –1409 mg/L and broadening crop suitability. Strategy 3 operates the WWTP at roughly half capacity (3.0 MCM/d) and supplements canal inflow with additional low-salinity drainage obtained by expanding the reuse of drains that are currently only partially reused along El-Salam Canal. This configuration maintains canal TDS at 1165–1205 mg/L (about 33–38% above baseline), a range compatible with many cereals, vegetables, and fruit trees when combined with appropriate leaching, while substantially reducing energy and chemical consumption.

Keywords: Water scarcity, Water Quality, sustainable water management policies, Agricultural Drainage Water reuse (ADWR), Bahr El-Baqar wastewater treatment plant..

1. Introduction

Water scarcity is a critical challenge of the twenty-first century, with over 1.8 billion people worldwide expected to face absolute scarcity by 2025 [1]. The Middle East and North Africa (MENA) region is among the most severely impacted, possessing only 1% of the world's freshwater resources [2]. Currently, 83% of the MENA population suffers from extreme water stress, projected to encompass the entire population by 2050 [3]. Egypt exemplifies this crisis, with per capita water availability decreasing from 570 m³ in 2018 to an estimated 390 m³ by 2050, well below the international scarcity threshold of 1,000 m³ [4]. This has created a gap between the national demand of 83.0 billion cubic meters and the conventional supply of 63.0 billion cubic meters annually [5].

In response, Egypt has prioritized Drainage Water Reuse (DWR) as a strategic resource, with agricultural drainage water contributing approximately 20.0 billion cubic meters annually [6]. This aligns with global trends in arid regions where agriculture consumes 70% of available freshwater [6]. Egypt applies several reuse approaches, including direct blending of drainage water with freshwater through either official or intermediate mixing, as well as tertiary treatment followed by discharge into irrigation canals [7]. The sustainability of these practices depends on maintaining adequate water quality and implementing robust monitoring systems that can assess compliance, temporal variability, and their implications for soil health and crop productivity [8].

Nevertheless, drainage water reuse faces significant challenges. Drainage water quality is often compromised by co-discharge of agricultural return flows, untreated or partially treated municipal effluents, and industrial discharges, which degrade drainage water quality and restrict its suitability for irrigation [9]. Salinity buildup is especially critical, driving soil salinization, inducing osmotic stress, and suppressing yields in salt-sensitive crops with low tolerance thresholds [10]. Mitigating salt accumulation requires additional freshwater for leaching, which paradoxically intensifies water scarcity pressures while lowering water use efficiency [11].

Egypt’s Bahr El-Baqar drain exemplifies these constraints. Historical data have exhibited high levels of salinity and pollution, which significantly restrict its suitability for safe agricultural reuse through direct mixing with freshwater, nor applied in agriculture under FAO guidelines. This degradation arises from the drain's extensive coverage across multiple governorates, resulting in continuous inflows of industrial effluents alongside treated and untreated municipal wastewater [12].

Consequently, Egypt inaugurated the Bahr El-Baqar Wastewater Treatment Plant (WWTP) in 2021, with capacity of 5.6 million Cubic meter /day (MCM/d) , treating water from Bahr El-Baqar, Shadr Azzam, and Om El-Reesh drains [13]. The treated effluent is discharged into the Sheikh Jaber Canal (El-Salam Canal), irrigating approximately 420,000 acres in Central Sinai. While the plant successfully improved most water quality parameters to meet Egypt's Law 48/1982, Article 49 standards, salinity remains a crucial limitation, threatening soil health, reducing crop yields, restricting the range of cultivable crops, and increasing freshwater requirements for leaching. Together, these effects reduce the overall irrigation efficiency within the El-Sheikh Jaber command area.

Addressing irrigation water salinity traditionally focuses on desalination technologies or agricultural management practices, including salt-tolerant crops, efficient irrigation methods, and leaching [14]. However, desalination remains prohibitively expensive for large-scale irrigation, while agricultural management approaches address symptoms rather than causes. Restricting crop selection limits agricultural diversity and economic returns, while leaching practices paradoxically increase freshwater demand. An alternative involves operational pre-treatment strategies that optimize source water blending before treatment. By strategically selecting and blending inflows from drains with varying salinity characteristics, influent salinity can be reduced cost-effectively.

However, existing research has not adequately explored the design and evaluation of operational blending scenarios for pre-treatment salinity management. Most studies focus on post-treatment water quality or agricultural adaptation without systematically investigating how operational maneuvering among drains with different salinity profiles can minimize influent salinity. Moreover, the relationship between achievable salinity levels through pre-treatment blending and suitable crop selection remains poorly defined. The Bahr El-Baqar plant exemplifies this gap; despite managing multiple current and potential drains with distinct salinity characteristics, no systematic framework exists to guide operational decisions on blending ratios, predict resulting salinity levels, or match outcomes with crop recommendations. Plant operators lack a decision-support framework to design and evaluate alternative pre-treatment blending scenarios that minimize salinity impacts on treatment efficiency and downstream agricultural productivity.

This study addresses this gap by developing an operational optimization framework for pre-treatment salinity management at the Bahr El-Baqar plant. The framework enables design and evaluation of alternative blending scenarios by integrating salt mass balance modeling with hydraulic constraints [15]. The specific objectives are to: (i) characterize salinity profiles of the current and potential source drains under varying conditions, (ii) design alternative pre-treatment blending scenarios through operational maneuvering, (iii) predict influent salinity levels for each scenario, (v) evaluate downstream impacts on the Sheikh Jaber Canal after mixing, and (iv) establish crop suitability recommendations based on predicted salinity levels.

This approach shifts salinity management from reactive post-treatment measures to proactive pre-treatment optimization, enabling dynamic adjustment of source contributions based on real-time data. The key contribution is linking operational blending decisions with both treatment performance and agricultural outcomes, eliminating the need for expensive desalination while expanding crop diversity options. While developed for Bahr El-Baqar, this methodology is transferable to other multi-source wastewater reclamation facilities in water-stressed regions.

2. DRAINAGE WATER REUSE PRACTICES

Agricultural Drainage Water Reuse (ADWR) is a central pillar of Egypt’s water and food security strategy and is widely practiced in the Nile Delta through official, unofficial and intermediate schemes [7], [16]. ADWR is organised along a quality-based ladder: when drainage water already complies with irrigation guidelines (e.g. FAO), it can be reused directly; when quality falls below direct-use standards but remains within the blending limits of the Egyptian Law 48/1982, reuse is achieved via rotational use (intra- or inter-seasonal alternation between drainage and freshwater according to crop tolerance) and controlled blending, with mixing ratios adjusted to monitored water quality and crop requirements.

For cases where water quality does not satisfy even the minimum criteria for blending, it must be treated, either by conventional secondary/tertiary processes or nature-based systems such as constructed wetlands, often followed by a final blending step to reach acceptable irrigation quality, albeit with higher costs or land requirements.

El-Salam Canal system operationalises this hierarchy by mixing drainage from Bahr Hadous, El-Serw, and Farskour with Nile water from the Damietta branch and by conveying tertiary-treated flows from Bahr El-Baqar, Shader Azzam, and Om El-Reish for final blending with Sheikh Jaber Canal water [17]. Despite this integrated configuration, conventional treatment at Bahr El-Baqar removes only a limited amount of salinity, so moderately to highly saline drainage waters still constrain reuse, revealing a critical technological gap and the need for cost-effective desalination options specifically tailored to agricultural drainage water.

3. Materials and Methods

This study adopts a structured methodological framework to evaluate salinity management strategies for the Bahr El-Baqar Wastewater Treatment Plant. The approach integrates hydrological characterization, salt mass balance modeling, operational blending scenarios, and canal mixing assessment, culminating in an optimization framework that identifies optimal strategies for sustainable reuse under hydraulic constraints.

3.1 Study Area

The Bahr El-Baqar Wastewater Treatment Plant (WWTP) is located in Sinai, Egypt, approximately 10 kilometers south of the Port Said tunnels and 17 kilometers east of El-Qantara city. As one of the world's largest wastewater treatment facilities, the plant has a total capacity of 5.6 million cubic meters per day (5.6 MCM/D), equivalent to 2.0 billion cubic meters annually (2.0 BCM/Y). Bahr El-Baqar WWTP specifically feeds the Sheikh Jaber Canal, the eastern extension of El-Salam Canal beyond the Suez Canal, supporting agricultural development under the North Sinai Agricultural Development Project (NSADP) [17], [18]. NSADP targets approximately 420,000 acres in northern and central Sinai, where water availability from existing sources was insufficient to meet irrigation demands [13] , [19].

The plant receives water from three main drains: Bahr El-Baqar, Shader Azzam, and Om El-Rish drain as shown in (Figure 1). These drains collect agricultural, industrial, and domestic wastewater from extensive catchment areas across multiple governorates. Due to the absence of alternative drainage outlets, the system must receive the entire discharge from both Shader Azzam and Om El-Reesh drains, while the remaining capacity is supplemented from Bahr El-Baqar drain to meet the plant's capacity.

Water collection operates through a sequential system where the gate at kilometer 27.6 of Bahr El-Baqar drain is closed while the mixing path gate is opened, directing flow into the mixing channel. Shader Azzam drain water is pumped via the Shader Azzam pumping station, and at kilometer 12.25, Om El-Reesh drain joins the system. The combined flow is then lifted by the New El-Salam pumping station (seven units, each 0.95 MCM/D capacity) and conveyed through four pipelines beneath the Suez Canal (3.8 m diameter each) [19].

The treatment process includes raw water pumping, flocculation, sedimentation, filtration, and disinfection, effectively addressing conventional pollutants from domestic, agricultural, and industrial sources. The Treated effluent is discharged directly into the Sheikh Jaber Canal immediately after crossing the Suez Canal. Despite the plant's advanced treatment capacity for conventional pollutants, salinity remains largely unaffected by the treatment process and poses the primary constraint for sustainable irrigation water reuse. Elevated salinity can cause adverse physiological effects on crops and reduce long-term soil productivity, making operational strategies to minimize influent salinity through pre-treatment blending optimization essential for enhancing water quality in the NSADP command area.

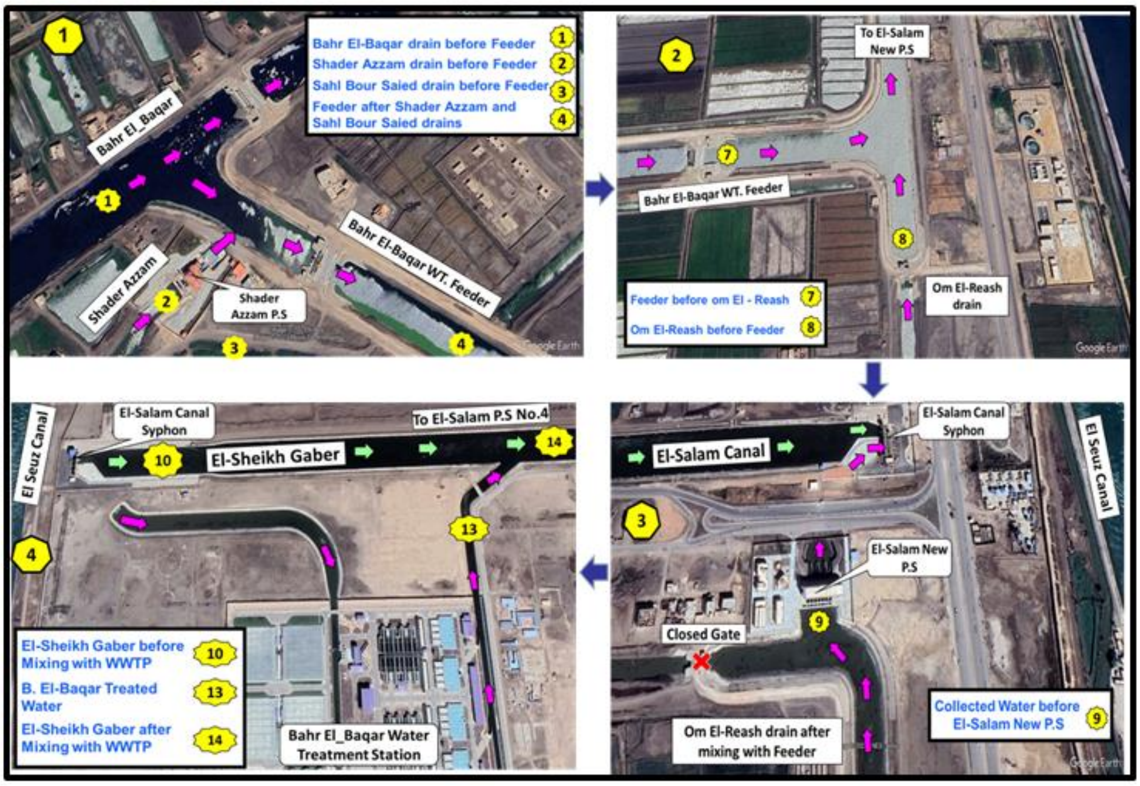

Fig. (1) Bahr El-Baqar wastewater treatment plant water system

3.2 Methodology

The study applies a structured conceptual framework (Figure 2) to systematically diagnose and optimize water management within the Bahr El-Baqar system. The process begins by mapping existing water sources, conveyance elements, and operating policies. This baseline evaluation is supported by multiple field visits and environmental data collection efforts, which facilitate the identification of current constraints and the exploration of additional candidate water resources. This diagnostic stage is reinforced by field visits and targeted data collection to document site-specific constraints and to identify additional drainage water resources with potential for mobilization.

3.2.1 Potential Water Resources Investigation

Extensive field investigations were conducted at the Bahr El-Baqar water treatment plant and surrounding areas to identify salinity-management options based on modified source blending. Several agricultural drains, including El-Ghazlan, North Ismailia and South Sahl Port Said, were identified as suitable candidates to partially or fully substitute high-salinity drains such as Shader Azzam. Additional drains (El-Maria, Sahl El-Hosinia, El-Ahmadia and El-Tawel) were recognised as appropriate for direct integration with El-Salam Canal, thereby reducing the saline fraction conveyed from the Bahr El-Baqar treatment system, while further reuse potential was found in the currently reused Hadous, El-Serw and Farskour drains that still discharge significant volumes to Lake Manzala.

Discharge (Q) and Total Dissolved Solids (TDS) were systematically measured in all identified drains to quantify their suitability for integration into the canal system, and a dedicated monitoring network was subsequently established along these drains to ensure continuous observation of flow and salinity dynamics.

3.2.2 Monitoring Network Layout for Flow and Salinity Measurements

In this study, establishing a quantity-and-salinity monitoring network is a prerequisite for ensuring the long-term sustainability of the Bahr El-Baqar water-reuse project. The initial design of the network focused on drains that could potentially replace highly saline sources such as Shader Azzam and Om El-Reish, either through blending within the Bahr El-Baqar treatment system or by direct mixing with El-Salam Canal. In addition, a set of monitoring locations was distributed along the mixing path to provide the data required for model development and scenario analysis.

The initial monitoring network comprised 14 locations for flow and salinity measurements covering the entire project area, as shown in (Figure 3). These locations included the main agricultural drains: Bahr El-Baqar, Shader Azzam, Shamal Ismailia, El-Ghazlan, Sahl Port Said, El-Mataria, and Om El-Rish. Furthermore, three locations were selected along the feeder path downstream of each proposed mixing point, in addition to one location immediately downstream of the treatment plant outlet, two locations on El-Salam Canal situated upstream and downstream of the Bahr El-Baqar WWTP mixing point with the canal, and one location upstream of the proposed mixing point associated with the El-Mataria pump station.

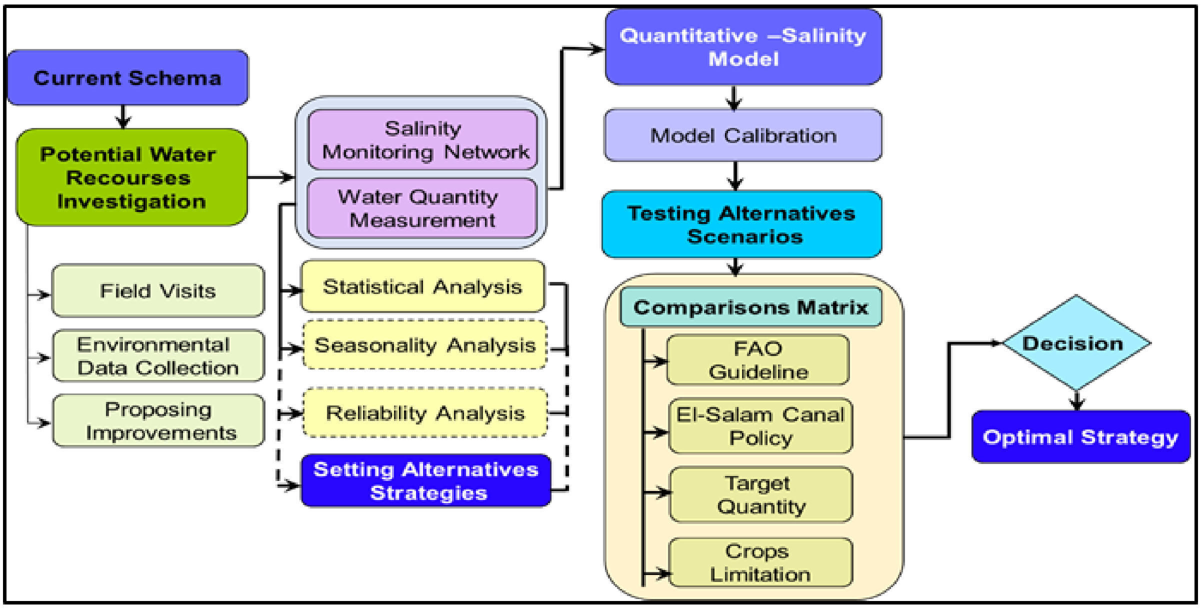

Fig. (2) Data-driven framework for drainage water reuse assessment

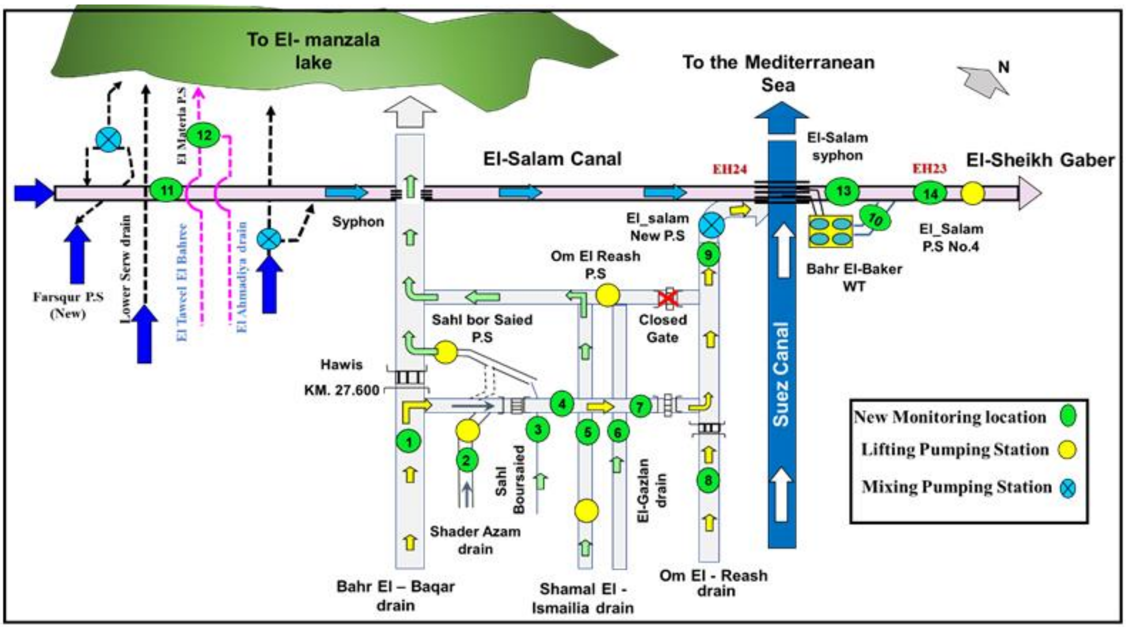

Fig. (3) Layout of the flow and salinity monitoring network in the study area

3.2.3 Statistical Analysis of Seasonal Salinity Data

The collected water quality data are statistically analyzed to assess salinity dynamics across the project sites. Descriptive statistics, including the mean and standard deviation, are first computed for each water source and season to summarize central tendency and variability in salinity. However, relying solely on mean values may inadequately represent data variability and distribution, especially in the presence of skewness and extreme events. Therefore, a more robust statistical approach is adopted whereby the 95th percentile is calculated for each water source and season to enhance reliability and confidence in the assessment while minimizing the influence of outliers.

Additionally, the dataset is stratified into summer and winter periods to account for seasonal impacts on salinity levels and to enable evaluation of temporal variations within the monitoring results.

3.2.4 Setting Alternatives Operational Strategies for B. El-Baqar WWTP

In this step, the qualitative investigation and monitoring data are translated into a structured set of realistic operating options for the Bahr El-Baqar system. Three main strategies were formulated, as summarized in Figure 4, each representing a distinct operational philosophy that addresses different management priorities and infrastructure constraints. The selection of these three strategies was designed to span the realistic management space of the system while reflecting technically feasible and operationally relevant options.

Strategy 1 represents the baseline approach that maximizes utilization of existing infrastructure without requiring new investments or modifications to the drainage network. This strategy reflects the current operational mandate to receive the entire discharge from Shader Azzam and Om El-Reesh drains due to the absence of alternative drainage outlets, with remaining capacity supplemented from Bahr El-Baqar drain. Seven scenarios (one through seven treatment units) were defined under this strategy, maintaining the existing source configuration across all capacity levels.

Strategy 2 was selected to evaluate whether systematic source substitution can achieve salinity targets without expensive desalination. This strategy prioritizes water quality by replacing high-salinity sources (Shader Azzam and Om El-Rish) with lower-salinity alternatives (Bahr El-Baqar and Sahl Bour Saied) as treatment capacity increases. The replacement hierarchy ensures the WWTP influent is composed exclusively of lower-salinity sources throughout all scenarios, representing the upper bound of achievable salinity reduction through pre-treatment blending optimization alone.

Strategy 3 explores a hybrid approach where the WWTP operates at approximately 50-55% of design capacity (3.0 MCM/day) using only Bahr El-Baqar drain, while the remaining demand at Sheikh Jaber Canal is met by directly mixing from Mataria pumping station (El-Ahmadia, El-Tawel Bahary, El-Tawel Qebly), Farskour, and El-Serw into the canal downstream. This strategy was selected to test whether reduced-capacity WWTP operation combined with downstream intermediate mixing can achieve better salinity while reducing energy consumption and operational costs compared to full-capacity tertiary treatment of all available drainage water.

Collectively, these strategies differ in source selection (fixed, optimised, or diversified), WWTP loading (full or partial), and mixing location (pre-treatment only or combined with downstream canal mixing). This structured design supports robust scenario modelling and comparison, helping to identify operationally feasible strategies that balance water quantity, quality, infrastructure use, and costs.

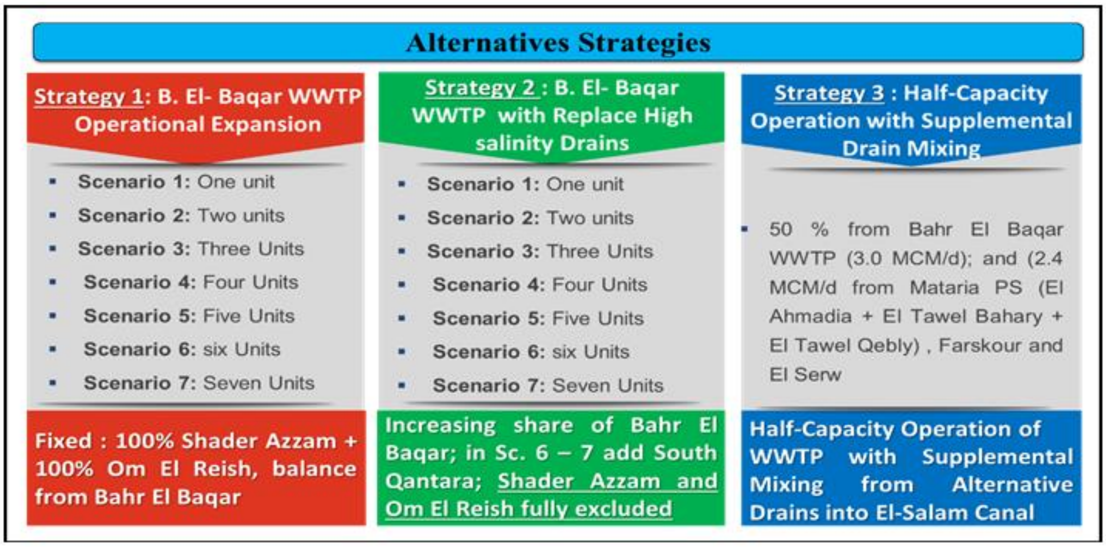

Fig. (4) Alternative strategies for salinity mitigation at El-Salam Canal.

3.2.5 Quantitative and Salinity Model

Water quality models are essential tools for understanding and predicting water quality dynamics. In Bahr El-Baqar system, most conventional water quality parameters (organic matter, nutrients, pathogens) are substantially reduced by the advanced treatment processes, whereas salinity remains largely unaffected and continues to pose the primary constraint for reuse. Given that salinity behaves conservatively and is predominantly governed by point-source inputs and mixing processes, a dedicated salinity-focused model was developed.

A quantitative salinity model (Figure 3) was established to simulate the integrated water system under different management scenarios and mixing arrangements. The model aims to provide reliable estimates of salinity levels at key locations for each scenario, thereby supporting the design of sustainable water management strategies.

3.2.5.1 Model Assumptions

The salinity model is formulated under the following assumptions:

- **Conservative salts:** dissolved salts behave conservatively, with no significant reactions or transformations.
- **Complete mixing:** flows are instantaneously and completely mixed at all confluence points.
- **Quasi-steady state:** discharges and concentrations are steady within each simulation period.
- **Point-source control:** salinity variations are dominated by the specified point inflows and their mixing, while diffuse inputs are neglected.

3.2.5.2 Mathematical Formulation

The mathematical formulation is based on salt load calculations and mass balance principles. The salt load (SL) at any location is defined as:

$$SL_1 = C_1 * Q_1 \qquad \text{(Eq.1)}$$

where SL_1 = salt load (tons/day), C_1 = salt concentration (mg/L), and Q_1 = discharge (MCM/day).

The rate of change of salinity within a control volume is governed by the difference between inflowing and outflowing salt loads, accounting for mixing at confluence points. For a mixing point receiving inflows from multiple sources, the resulting concentration is calculated using mass balance:

Mixed water at the feeder after B. El-Baqar, Shader Azzam, and Bour Saied mixing (Node 4), Eq. 2-3

$$C_4 = \frac{(SL_1 + SL_2 + SL_3)}{(Q_1 + Q_2 + Q_3)} \qquad \text{(Eq.2)}$$

$$Q_4 = Q_1 + Q_2 + Q_3 \qquad \text{(Eq.3)}$$

where:

- C_4: mixed salinity concentration after B. El-Baqar, Shader Azzam, and Bour Saied mixing (mg/L).
- Q_4: collected total flow after B. El-Baqar, Shader Azzam, and Bour Saied mixing (MCM/day).
- SL_1, SL_2, SL_3: salt loads from Bahr El-Baqar drain, Shadr Azzam drain, and Sahl Port Said drains, respectively (tons/day).
- Q_1, Q_2, Q_3: flow rates from Bahr El-Baqar drain, Shadr Azzam drain, and Sahl Port Said drains, respectively (MCM/day).
- C_1, C_2, C_3: salinity concentrations in respective source drains (mg/L)

Mixed water at the feeder after Shamal El-Ismalia and El-Gazlan drains mixing (Node 7), Eq. 4-5

$$C_7 = \frac{(SL_4 + SL_5 + SL_6)}{(Q_4 + Q_5 + Q_6)} \qquad \text{(Eq.4)}$$

$$Q_7 = Q_4 + Q_5 + Q_6 \qquad \text{(Eq.5)}$$

where:

- C7: mixed salinity concentration at the feeder after Shamal El-Ismalia and El-Gazlan drains mixing (mg/L).
- Q_7: collected total flow at the feeder after Shamal El-Ismalia and El-Gazlan drains mixing (MCM/day).
- SL_4, SL_5, SL_6: salt loads at Node 4, Shamal El-Ismalia drain, and El-Gazlan drain, respectively (tons/day).
- Q_4, Q_5, Q_6: flow rates at Node 4, Shamal El-Ismalia drain, and El-Gazlan drain, respectively (MCM/day).
- C_4, C_5, C_6: salinity concentrations in respective source drains (mg/L).

Pre-Treatment Mixing at WWTP Intake (Node 9), Eq. 6-7

$$C_9 = \frac{(SL_7+SL_8)}{(Q_7+Q_8)} \quad \text{(Eq.6)}$$

$$Q_9 = Q_7 + Q_8 \quad \text{(Eq.7)}$$

where:

- C_9: mixed salinity concentration at WWTP Intake (mg/L).
- Q_9: collected total flow at WWTP Intake (MCM/day).
- SL_7, SL_8: salt loads at Node 7, Om El-Reash drain, respectively (tons/day).
- Q_7, Q_8: flow rates at Node 7, and Om El-Reash drain, respectively (MCM/day).
- C_7, C_8: salinity concentrations in respective source drains (mg/L).

Final Mixing in El-Sheikh Gaber canal - El-Salam Canal (Node 14), Eq. 8-9

$$C_{14} = \frac{(SL_{10}+SL_{13})}{(Q_{10}+Q_{13})} \quad \text{(Eq.8)}$$

$$Q_{14} = Q_{10} + Q_{13} \quad \text{(Eq.9)}$$

where:

- C_{14}: mixed salinity concentration at El-Sheikh Gaber canal after WWTP mixing (mg/L).
- Q_{14}: collected total flow at at El-Sheikh Gaber canal after WWTP mixing (MCM/day).
- SL_{10}, SL_{13}: salt loads at El-Sheikh Gaber canal after the syphon, and effluent of B. El-Baqar WWTP, respectively (tons/day).
- Q_{10}, Q_{13}: flow rates at El-Sheikh Gaber canal after the syphon, and effluent of B. El-Baqar WWTP, respectively (MCM/day).
- C_{10}, C_{13}: salinity concentrations in respective source drains (mg/L).

The numbering of nodes and locations corresponds to the schematic diagram presented in Figure 3, which illustrates the complete water system configuration including all source drains, mixing points, treatment facilities, and canal reaches.

3.2.5.3 Model Application

The model was applied to evaluate multiple operational scenarios by varying the relative contributions (flow rates) from the several source drains. For each scenario, the model calculates: Mixed influent salinity at the WWTP intake (C_4), Salinity levels at downstream mixing points (C_7, C_9), and Final salinity in the El-Salam Canal delivery point (C_{14}). The scenarios were designed to identify optimal blending ratios that minimize salinity levels throughout the system while respecting hydraulic and operational constraints.

4. Results and Discussion

4.1 Data Analysis; Seasonal Variability and Data Reliability

The salinity dataset (August 2022–July 2024) reveals pronounced seasonal patterns in total dissolved solids (TDS). Descriptive statistics and seasonal 95th percentiles were computed for each drain to provide conservative operational indicators.

Bahr El-Baqar drain, the main source with 95th-percentile discharge of 4.63 MCM/day, exhibits moderate mean TDS of 1420 mg/L with limited seasonal variation (summer: 1490 mg/L; winter: 1390 mg/L). Values remain below the 2000 mg/L limit of Egyptian Law 48, indicating stable and compliant conditions (Figure 5). In contrast, Shader Azzam drain shows severe salinity stress (mean: 4404 mg/L; summer 95th percentile: 4700 mg/L), exceeding legal limits threefold, while Om El-Reesh exhibits intermediate levels (mean: 2828 mg/L; summer/winter 95th percentiles: 3005/2720 mg/L) with the largest seasonal difference among these drains. Despite their small discharges (0.27 and 0.31 MCM/day respectively; Figure 6), these two drains transport high salt loads.

Among drains connected to the treatment system, Sahl Port Said and El-Ghazlan display markedly lower salinities (means: 2180 and 1863 mg/L; summer 95th percentiles: 2375 and 2215 mg/L), indicating partial Law 48 compliance during peak conditions with seasonal differences of 200-400 mg/L. Conversely, Shamal El-Ismailia exhibits the highest salinity in the network (mean: >5500 mg/L; summer 95th percentile: 5720 mg/L), requiring careful consideration in blending strategies.

Drains currently discharging partially to Lake Manzala (Bahr Hadous, El-Serw, and Farskour) represent potential resources for expanded reuse. Bahr Hadous shows mean TDS of 1269 mg/L (summer/winter 95th percentiles: 1420/1370 mg/L), while El-Serw and Farskour exhibit even lower means (695 and 625 mg/L) with 95th percentiles of

820/735 mg/L and 785/685 mg/L respectively. All values remain safely below Law 48 limits, suggesting residual discharges could be systematically integrated into future mixing schemes with limited salinity constraints.

To assess the robustness of the design statistics, an uncertainty and sensitivity analysis was performed on the TDS time series for all drains. For each source, the coefficient of variation (CV) ranged from 9 – 12% (CV = 0.07 – 0.10) for low-salinity drains (Bahr El-Baqar, El-Serw, and Farskour to 16 – 22% (CV = 0.16 – 0.22) or high-salinity ones (Shader Azzam, Om El-Reish, and Shamal El-Ismailia), while interquartile ranges (IQR) spanned 200 – 390 mg/L for stable sources versus 750 – 1150 mg/L for variable ones, indicating greater TDS fluctuations in saline drains. The seasonal 95th percentile ensures robust design under peak salinity. Drains span a continuum: extreme (Shamal El-Ismailia, Shader Azzam), elevated (Om El-Reish), moderate (Bahr El-Baqar, Sahl Port Said), and low-risk (Farskour, El-Serw, El-Tawel) for blending/reuse.

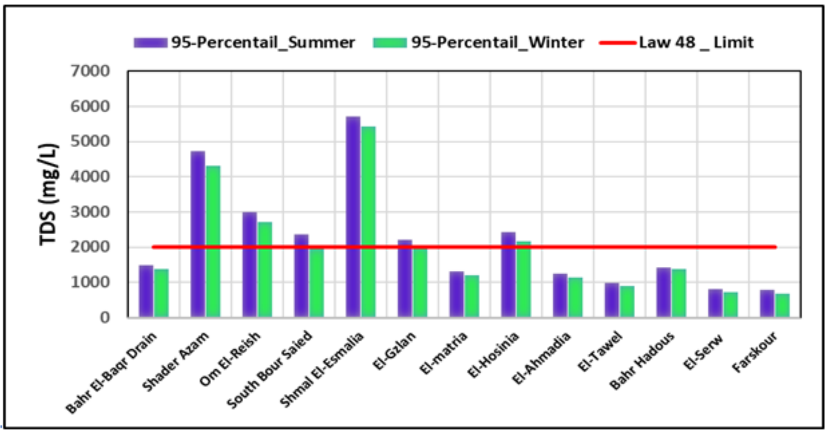

Fig. (5) Seasonal salinity profiles of main drains relative to Law 48 threshold.

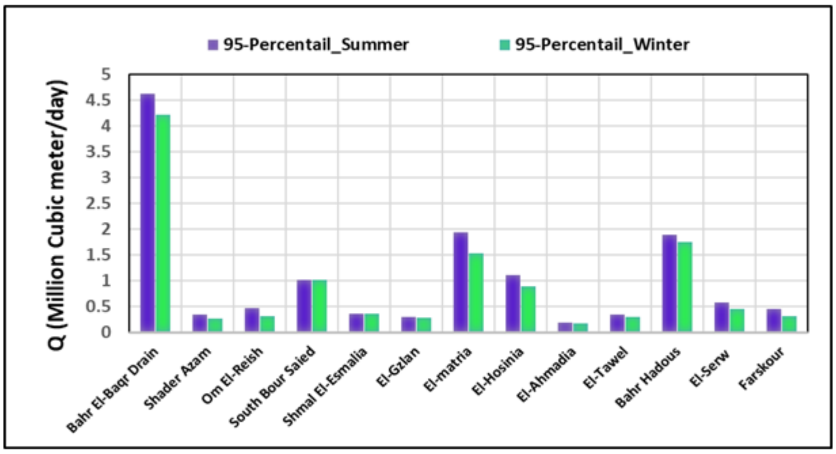

Fig. (1) 95th-percentile summer and winter discharges of the main drains, expressed in million cubic metres per day (MCM/d).

4.2 Observed Operation of the Bahr El-Baqar and El-Salam Canal System

The trial operation of the Bahr El-Baqar treatment Plant revealed that the average flow collected at the newly commissioned El-Salam pumping station, before conveyance to the Bahr El-Baqar wastewater treatment plant (WWTP), was approximately 0.80 MCM/d. Of this, 0.27 MCM/d originated from Shader Azzam (representing 100% of the drain's flow), 0.31 MCM/d from Om El-Reish (100% of the drain's flow), and only 0.22 MCM/d from Bahr El-Baqar drain, equivalent to about 5% of the drain's total discharge. Collectively, these contributions represent merely 14% of the design target capacity of 5.6 MCM/d.

The collected inflows to the Bahr El-Baqar WWTP exhibit elevated salinity, with total dissolved solids (TDS) ranging from 2,870 mg/L in winter to 3,140 mg/L in summer. These concentrations exceed widely applied guidelines for large-scale drainage water reuse, particularly given that the Bahr El-Baqar WWTP achieves only limited salt removal. Upstream of the mixing point, El-Salam Canal conveys an average flow of 1.78 MCM/d with a mean TDS of approximately 875 mg/L. Following blending with effluent from the Bahr El-Baqar WWTP, canal salinity rises sharply, by 71% in winter (to 1,500 mg/L) and 81% in summer (to 1,585 mg/L). This marked increase demonstrates the dominant influence of the current treatment-and-mixing configuration on the salinity regime of El-Salam Canal. These findings highlight a critical operational challenge as the present (partial-operation) configuration substantially elevates salinity levels, undermining reuse potential and irrigation suitability, and underscoring the need to reconsider source selection and optimise blending ratios.

Model calibration and validation were conducted to strengthen confidence in the results. Calibration was performed for the period from Februaryto July 2022, while validation was extended to cover (Augest 2022 – January 2023) to strengthen confidence in the results. As illustrated in Figure 7, measured monthly TDS values in the El-Sheikh Gaber reach (downstream of the WWTP) closely align with model predictions across both calibration (February–July 2022). The model successfully reproduces both the magnitude and seasonal dynamics of TDS, capturing the late-winter peak, the spring minimum, and the subsequent rise toward early summer, as well as the stabilization observed in autumn.

Quantitatively, calibration performance was robust, with a Root Mean Square Error (RMSE) of 44 mg/L, a Coefficient of Determination (R^2 = 0.94), and a Nash–Sutcliffe Efficiency (NSE = 0.90). Validation statistics further confirmed model reliability, with Root Mean Square Error (RMSE = 57 mg/L), Coefficient of Determination (R^2 = 0.91), Mean Absolute Error (MAE = 35 mg/L), and Percent Bias (PBIAS = –3.10%), indicating only minor underestimation of observed values. Collectively, these metrics demonstrate that the model explains nearly all of the observed variability in TDS at this location, while faithfully representing seasonal salinity fluctuations.

This high level of agreement provides confidence that the calibrated and validated model can be applied to evaluate alternative blending strategies and source-replacement scenarios, thereby offering a reliable basis for operational decision-making under the Bahr El-Baqar treatment system.

4.3 Scenario Analysis: Operating Policies for Bahr El-Baqar Treatment Plant

4.3.1 Baseline irrigation water salinity at El-Salam Canal upstream of the Bahr El-Baqar WWTP

Baseline irrigation water salinity values (TDS) were derived from the National Monitoring Network for Water Quantity and Quality in Nile Delta canals and drains. Monthly field and laboratory measurements collected between August 2022–July 2024 characterize inflows to El-Salam Canal upstream of the Bahr El-Baqar WWTP, yielding a baseline TDS of <875 mg/L. This baseline represents the reference condition against which salinity scenarios were evaluated.

4.3.2 First Strategy; Operational Unit Expansion

The first strategy assessed operational capacity expansion of the Bahr El-Baqar WWTP without modifying existing infrastructure or excluding any drain. Seven scenarios were simulated with station discharge increasing stepwise from 0.8 to 5.21 MCM/day through successive addition of treatment units, while maintaining full flows from Shader Azzam and Om El-Reesh drains (0.58 MCM/day combined) with remaining capacity supplied from Bahr El-Baqar drain.

Simulations (Table 1) revealed an inverse relationship between treated discharge and effluent salinity: TDS at the plant outlet decreased from 2871/3143 mg/L (summer/winter) in Scenario 1 to 1621/1748 mg/L in Scenario 7. However, post-mixing values in El-Salam Canal remained persistently elevated compared to baseline (875–930 mg/L). Scenario 1 produced 1,500 –1,585 mg/L (+71 –81%), while Scenario 7 achieved only marginal improvement to 1,431–1,525 mg/L, representing merely 4.6 –3.8% reduction despite a 6.5-fold capacity increase. The fixed 0.58 MCM/day high-salinity component contributed an irreducible salt burden of approximately 2,088 metric tons daily regardless of system expansion.

According to FAO guidelines, sensitive crops such as beans, citrus, grapes, and strawberries cannot be cultivated under these salinity levels, while moderately tolerant crops (e.g., maize, sunflower, and tomato) would suffer yield reductions. Only highly tolerant crops such as barley, cotton, and sugar beet could be sustained without significant productivity loss. Overall, canal salinity under all scenarios remained 60 – 70% higher than the original pre-mixing level, well above typical irrigation guidelines. Thus, meaningful protection of El-Salam Canal water quality will require source substitution, blending strategies, and enhanced leaching practices, rather than operational adjustments alone.

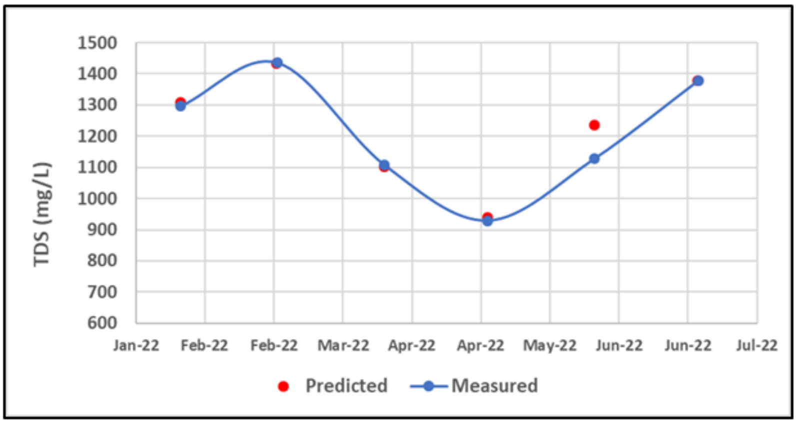

Fig. (7) Calibration of simulated versus measured TDS at El-Sheikh Gaber reach (February–June 2022).

Table 1: Seasonal TDS values at the WWTP and El-Sheik Gaber across the Scenarios of the First Strategy.

Scenario	Q _ WWTP (MCM/d)	TDS (mg/l) from WWTP		TDS (mg/l) _ El-Sheik Gaber after mixing with WWTP	
		Winter	Summer	Winter	Summer
Scenario 1 _ 1 unit	0.8	2871	3143	1500	1585
Scenario 2 _ 2 unit	1.6	2142	2329	1474	1563
Scenario 3 _ 3 unit	2.4	1884	2042	1458	1549
Scenario 4 _ 4 unit	3.2	1758	1901	1446	1539
Scenario 5 _ 5 unit	4	1690	1825	1439	1533
Scenario 6 _ 6 unit	4.8	1641	1770	1433	1528
Scenario 7 _ 7 unit	5.21	1621	1748	1431	1525

Note: Q_WWTP represents the flow rate from wastewater treatment plant; TDS values are expressed in (mg/L).

4.3.3 The Second Strategy: Alternative Operating Policies and Source Substitution Strategy

The second strategy progressively replaced high-salinity Shader Azzam and Om El-Reesh drains with lower-salinity sources (Bahr El-Baqar and South Qantara) while approaching the WWTP design capacity of 5.6 MCM/day. Seven scenarios were evaluated at 95th-percentile confidence levels for both winter and summer conditions (Table 2).

Scenarios 1–5 employed only Bahr El-Baqar drain, with its proportion increasing from 18% (0.8 MCM/day) to 87% (4.0 MCM/day). The 95th-percentile TDS at the WWTP outlet remained stable at 1390–1490 mg/L in both seasons. Mixed TDS at El-Sheikh Gaber increased from baseline (875 mg/L) to 1039–1302 mg/L, with higher summer values. Importantly, these levels remained substantially lower than Strategy 1 results and stayed within FAO reuse thresholds.

Scenarios 6,7 incorporated South Qantara drain to approach design capacity. Scenario 6 combined 100% Bahr El-Baqar (4.63 MCM/day) with 20% South Qantara (0.17 MCM/day), yielding 4.8 MCM/day total flow with effluent TDS of 1408/1510 mg/L (winter/summer) and canal salinity of 1265/1339 mg/L, safely below 1.5 g/L. Scenario 7 reached full capacity (5.6 MCM/day) using all Bahr El-Baqar with 100% South Qantara (1.0 MCM/day), producing effluent TDS of 1467/1577 mg/L and canal salinity of 1325/1409 mg/L. This represented a 50–60% increase over baseline but was achieved under significantly higher volumes without high-salinity drains.

The source-substitution strategy demonstrates that replacing Shader Azzam and Om El-Reesh enables the WWTP to approach design capacity while maintaining El-Sheikh Gaber TDS below 1500 mg/L under 95th-percentile conditions, a marked improvement over the original configuration. However, resulting salinity still exceeds the original canal baseline and requires evaluation against specific policy targets, particularly regarding crop restrictions under FAO guidelines.

4.3.4 Third Strategy: Re-allocating Low-Salinity Drains to Enhance Canal Water Quality

This third strategy operates the Bahr El-Baqar WWTP at approximately half of its design capacity while still meeting the full target supply to El-Salam Canal by substituting additional low-salinity drainage sources. In this configuration, the plant treats about 3.0 MCM/d drawn entirely from the Bahr El-Baqar drain, whose moderate salinity yields effluent TDS of 1390 mg/L (winter) and 1490 mg/L (summer).

The remaining 2.4 MCM/d required to reach the design delivery to El-Salam Canal is supplied without new infrastructure by reallocating existing drainage flows: approximately 2.0 MCM/d from the Mataria pumping station (aggregating El-Ahmadia, El-Tawel Bahary, and El-Tawel Qebly), about 0.25 MCM/d from Farskour (currently discharged to Lake Manzala), and 0.40 MCM/d from El-Serw, while still allowing 0.27 MCM/d from El-Serw to reach the lake.

After mixing with El-Sheikh Gaber Canal, TDS at the 95th percentile rises from the baseline value of 875 mg/L to 1165 mg/L (winter) and 1205 mg/L (summer) levels markedly lower than those observed in scenarios relying on the highly saline Shader Azzam and Om El-Rish drains. This reconfiguration therefore achieves the target canal inflow through a combination of partially treated moderate-salinity water and untreated but relatively low saline drainage, while avoiding any rerouting of Shader Azzam or Om El-Reish and requiring no additional conveyance works.

From a performance perspective, the strategy maintains El-Sheikh Gaber salinity at 1200 mg/L under both winter and summer 95th-percentile conditions. These levels remain acceptable for many crops when accompanied by appropriate leaching and management practices, and are substantially lower than those produced when high-TDS drains dominate the WWTP influent. Economically, halving the WWTP operating load implies significant savings in energy and chemical consumption.

Overall, this strategy offers a cost-effective compromise as it maintains the required supply volume, significantly improves canal water quality compared with the original configuration, and achieves these outcomes through operational adjustments to existing infrastructure only, without the need for new conveyance systems.

Table 2: Seasonal TDS values at the WWTP and El-Sheik Gaber across the Scenarios of the Second Strategy

Scenario	Water Resources	Q _ WWTP (MCM/day)	TDS (mg/l) after WWTP		TDS (mg/l) _ El-Sheik Gaber after mixing with WWTP	
			Winter	Summer	Winter	Summer
Scenario 1 _ 1 unit	18% B. El-Baqar	0.8	1390	1490	1039	1071
Scenario 2 _ 2 unit	35% B. Elbaqar	1.6	1390	1490	1120	1168
Scenario 3 _ 3 unit	53% B. Elbaqar	2.4	1390	1490	1173	1231
Scenario 4 _ 4 unit	70% B. Elbaqar	3.2	1390	1490	1207	1272
Scenario 5 _ 5 unit	87% B. Elbaqar	4	1390	1490	1232	1302
Scenario 6 _ 6 unit	100% B. Elbaqar + 20% Sahl Port Saied	4.8	1408	1510	1265	1339
Scenario 7 _ 7 unit	100% B. El-Baqar+ 100% Sahl Port Saied	5.6	1467	1577	1325	1409

4.3.5 Uncertainty Propagation in Blending Scenarios

A sensitivity analysis evaluated the impact of ±10% TDS perturbations on blended water quality across key scenarios: for mixes dominated by Bahr El-Baqr (70–80% contribution), output TDS varied by ±2–4%; moderate blends with Sahl Port Said/El-Ghazlan showed ±5–7% shifts; but high-saline scenarios (≥30% Shader Azzam or Shmal El-Ismailia) produced ±9–12% uncertainty, underscoring the need for dilution buffers in those cases

These quantitative ranges confirm the seasonal 95th percentile as a conservative metric, with low-uncertainty drains suitable for reliable blending and high-variability ones requiring operational safety margins of 10–15%.

4.4 Agronomic Implications of the El-Sheikh Gaber Salinity Scenarios

The comparative assessment of the four salinity scenarios at El-Sheikh Gaber demonstrates differentiated agronomic implications, as presented in Table 3. To expand the analysis quantitatively, crop yield responses were estimated using published salinity–yield functions that relate irrigation water salinity (TDS or Electrical conductivity (ECw) to relative yield. Results indicate that salt-tolerant crops such as wheat, rice, and olive orchards maintain near-optimal yields under all scenarios, with negligible reductions even at TDS levels approaching 1,600 mg/L. In contrast, sensitive crops such as potato and berseem clover exhibit measurable yield penalties once irrigation water exceeds 1,200–1,400 mg/L. At irrigation water salinity levels of around 1,400 mg/L, potato yields are expected to decrease by about 3–5%, whereas berseem clover performance becomes marginal, indicating that its cultivation is only feasible with careful management under the first strategy.

In addition, leaching requirements were estimated using FAO guidelines, expressed as the fraction of additional freshwater needed to maintain acceptable root-zone salinity when irrigating with higher-TDS water. At TDS levels of 1,200 mg/L, citrus orchards require approximately 10 – 15 % extra freshwater for leaching, while tomato requires aboyt 15 –20 %. These quantitative estimates highlight the operational importance of maintaining blended water below 1,200 mg/L to minimize yield penalties and excessive leaching demands.

4.5 Comparative Assessment of Alternative Operating Strategies

The comparative analysis, presented in Table 4, reveals fundamental differences in performance among the three strategies. Strategy 1, despite achieving a 6.5-fold capacity increase, yielded only marginal salinity improvements (4.6% reduction) due to the fixed high-salinity load from Shader Azzam and Om El-Rish drains (2,088 tons/day). The resulting TDS levels of 1431–1585 mg/L consistently exceeded FAO irrigation thresholds, restricting cultivation to highly salt-tolerant crops only. Strategy 2 addressed this limitation through source substitution, eliminating high-salinity drains and maintaining El-Sheikh Gaber TDS within 1039–1409 mg/L across all capacity levels. This approach enabled operation at full design capacity (5.6 MCM/d) while significantly expanding crop suitability, though salinity remained 19 – 61% above baseline levels.

Strategy 3 achieved the optimal balance by operating at approximately half capacity (3.0 MCM/d) while supplementing supply with low-salinity drainage sources. This configuration-maintained TDS at 1165–1205 mg/L, representing only a 33–38% increase over baseline, substantially lower than the first Strategy 60–81% increase. Importantly, this approach provided the widest agricultural flexibility while reducing operational costs by approximately 50% compared to full-capacity operation.

These findings demonstrate that source quality management is more effective than capacity expansion for achieving water quality targets in mixed-influent treatment systems. Strategy 3 emerges as the most sustainable option, requiring no new infrastructure while delivering superior water quality and cost efficiency.

Table 3: Qualitative suitability of selected Egyptian crops under the four Strategies.

Crop	**Baseline (TDS < 875 mg/L)**	**Strategy 1: (1585 mg/L)**	**Strategy 2: (Max TDS 1400 mg/L)**	**Strategy 3: (Max TDS = 1200 mg/L**
Wheat	Suitable – no yield reduction expected	Suitable – well below tolerance	Suitable – well below tolerance	Suitable – well
Maize (grain)	Suitable –100% yield	Moderately suitable – slight yield loss possible at upper range	Suitable – up to (75–100% yield)	Suitable –100% yield
Rice (paddy)	Suitable – 100% yield	Suitable – within recommended range	Suitable – within recommended range	Suitable – within recommended range
Potato	Suitable – 100% yield	Moderately suitable – slight to moderate loss	Moderately suitable – slight loss near upper band	Suitable – 100%
Tomato	Suitable – 100% yield	Suitable to moderately suitable	Suitable – 100% yield	Suitable – 100% yield
Citrus (orange)	Suitable – 100% yield	Suitable to moderately suitable (needs leaching)	Suitable – especially <1400 mg/L	Suitable – good, with normal leaching
Olive	Highly suitable – very tolerant	Highly suitable – well within tolerance	Highly suitable – well within tolerance	Highly suitable – well within tolerance
Berseem clover	Suitable – 100% yield	Marginal – noticeable yield loss	Marginal to not recommended	Suitable – 100% yield or slight loss

Table 4: Comparative Assessment of Alternative Operating Strategies for Bahr El-Baqar WWTP and El-Salam Canal.

Criterion	**Strategy 1: Operational Unit Expansion**	**Strategy 2: Source Substitution**	**Strategy 3: Low-Salinity Drain Reallocation**
WWTP Capacity Utilized	0.8 – 5.21 MCM/d (14 – 93% of design)	0.8–5.6 MCM/d (14 –100% of design)	3.0 MCM/d (54% of design)
Water Sources	Shader Azzam + Om El-Reish (0.58 MCM/d) + Bahr El-Baqar (balance)	Bahr El-Baqar + Sahl Port Saied (Scenarios 6, 7)	Bahr El-Baqar (3.0 MCM/d) + El-Mataria, Farskour, El-Serw (2.4 MCM/d)
El-Sheikh Gaber TDS (mg/L)	Winter: 1431–1500, Summer: 1525–1585	Winter: 1039–1325, Summer: 1071–1409	Winter: 1165, Summer: 1205
Salinity Increase vs. Baseline	60 –81% above baseline (875 mg/L).	19 –61% above baseline.	33–38% above baseline.
Crop Suitability	Only salt-tolerant crops (barley, cotton, sugar beet) without yield loss.	Broad suitability; most field crops and vegetables viable below 1200 mg/L.	Wide crop flexibility; suitable for wheat, maize, rice, vegetables, and fruit trees.
Operational Cost	Increases with capacity (energy, chemicals for up to 7 units).	Increases with capacity (energy, chemicals for up to 7 units).	Reduced (50% WWTP load saves energy and chemicals).
Limitations	Persistently elevated salinity; limited crop options; minimal improvement with expansion.	Salinity still 50–60% above baseline at full capacity.	Relies on the availability of low-salinity drainage sources.
Recommended Application	Not recommended as a standalone solution.	Suitable when maximizing treated water volume is a priority, and low-salinity sources are available.	Optimal for balanced water quality and cost efficiency; recommended for sustainable irrigation management.

5. Conclusion and Recommendations

5.1 Conclusion

This study evaluated three alternative operating strategies for the Bahr El-Baqar Wastewater Treatment Plant to optimize water quality in the El-Salam Canal irrigation system. The scenario analysis demonstrated that capacity expansion alone (Strategy 1) cannot overcome the fundamental constraint imposed by high-salinity source waters, with TDS levels remaining 60–81% above baseline despite a seven-fold increase in treatment capacity. The fixed salt load from Shader Azzam and Om El-Reish drains (2,088 tons/day) represents an irreducible burden that severely restricts crop selection and agricultural productivity

Source substitution (Strategy 2) significantly improved outcomes by eliminating high-salinity drains and incorporating Bahr El-Baqar and South Qantara sources, enabling full design capacity operation while maintaining TDS within 1039 – 1409 mg/L. However, the optimal solution emerged from Strategy 3, which operates at approximately half capacity while supplementing treated effluent with strategically reallocated low-salinity drainage sources. This approach achieved TDS levels of 1165 – 1205 mg/L, a 33–38% increase over baseline, while providing the widest agricultural flexibility and reducing operational costs by approximately 50%.

The findings underscore that integrated source quality management is more effective than capacity expansion for achieving water quality targets in mixed-influent treatment systems. Strategy 3, a dual approach of moderate treatment and low saline drainage supplementation, offers the most sustainable pathway for balancing water quantity, quality, and economic efficiency.

5.2 Implications for Practice and Policy

These results indicate that wastewater treatment alone is not sufficient to safeguard irrigation water quality, particularly when the influent is dominated by high-salinity drainage. Even with adequate hydraulic capacity, the persistence of elevated TDS in the effluent shows that treatment must be complemented by deliberate source selection and blending with fresh water or low-salinity drains. In practice, salinity management becomes a system-wide task: optimising the mix of contributing sources can keep canal TDS within a moderate range, reduce the risk of soil salinisation, and lower the need for costly advanced desalination. At the same time, maintaining TDS in this range preserves diversification options for farmers, allowing both staple field crops and higher-value vegetables and fruit trees to be grown with only limited yield penalties, rather than confining production to a narrow set of highly salt-tolerant species. These findings align with national water-reuse and land-reclamation policies and contribute to several Sustainable Development Goals.

5.3 Recommendations

Based on the comparative analysis, the following recommendations are proposed for immediate implementation and medium-term planning:

- Adopt Strategy 3 as the primary operating policy for Bahr El-Baqar WWTP, treating approximately 3.0 MCM/d from Bahr El-Baqar drain while supplementing supply with 2.4 MCM/d from Mataria, Farskour, and El-Serw drainage sources.
- Discontinue use of Shader Azzam and Om El-Reish drains in the El-Salam Canal system due to their disproportionate contribution to salinity load and agricultural restrictions.
- Establish real-time salinity monitoring at key locations including WWTP influent and effluent, El-Sheikh Gaber mixing point, and downstream canal reaches to enable adaptive management and early detection of water quality deviations.
- Develop crop-specific irrigation guidelines tailored to the expected TDS range of 1165–1205 mg/L under Strategy 3, including leaching requirements, drainage management, and appropriate crop rotations for different soil types.

5.4 Future Research

Future work should focus on two main directions. First, coupling the hydrosalinity model with crop-growth and economic modules would allow explicit optimisation of cropping patterns, leaching fractions and on-farm drainage investments under different water-quality scenarios. Second, integrating high-resolution remote sensing with data-driven techniques (e.g. machine-learning models) could improve near-real-time monitoring of water quality and soil-salinity hotspots, providing the information backbone for adaptive, basin-scale management of the Bahr El-Baqar–El-Salam system.

REFERENCES

[1] W. Musie and G. Gonfa, “Heliyon Fresh water resource , scarcity , water salinity challenges and possible remedies : A review,” Heliyon, vol. 9, no. 8, p. e18685, 2023, doi: 10.1016/j.heliyon.2023.e18685.

[2] A. M. O. El, F. M. Fayiah, S. S. Lam, and T. B. M. H. Butt, “The application of water – energy nexus in the Middle East and North Africa (MENA) region : a structured review,” Appl. Water Sci., vol. 12, no. 5, pp. 1–21, 2022, doi: 10.1007/s13201-022-01613-7.

[3] P. Droogers et al., “Water resources trends in Middle East and North Africa towards 2050,” pp. 3101–3114, 2012, doi: 10.5194/hess-16-3101-2012.

[4] K. T. Sibhatu and M. Qaim, “Rural food security, subsistence agriculture, and seasonality,” PLoS One, vol. 12, no. 10, pp. 1–15, 2017, doi: 10.1371/journal.pone.0186406.

[5] A. Fleifle and A. Allam, “Remediation of agricultural drainage water for sustainable reuse,” Handb. Environ. Chem., vol. 55, pp. 297–324, 2017, doi: 10.1007/698_2016_119.

[6] T. Hajjar, R. H. Mohtar, L. Abou, and S. F. Yanni, “Science of the Total Environment Treated wastewater reuse for irrigation in a semi-arid region ☆,” Sci. Total Environ., vol. 966, p. 178579, 2025, doi: 10.1016/j.scitotenv.2025.178579.

[7] E. Helal, M. Shaban, E. Abd El-Karim, and A. Ellayen, “A comprehensive management model to maximize the benefits of

agriculture drainage water reuse," Water Environ. Res., vol. 93, no. 9, pp. 1722–1733, 2021, doi: 10.1002/wer.1559.

[8] V. Phogat et al., "Impact of long-term recycled water irrigation on crop yield and soil chemical properties," vol. 237, no. February, p. 106167, 2020.

[9] R. Kama, J. Song, Y. Liu, A. Kader, M. Hamani, and S. Zhao, "Water Availability and Status of Wastewater Treatment and Agriculture Reuse in China : A Review," 2023.

[10] H. El-ramady et al., "Review of Crop Response to Soil Salinity Stress : Possible Approaches from Leaching to Nano-Management," 2024.

[11] M. Helmecke, E. Fries, and C. Schulte, "Regulating water reuse for agricultural irrigation: risks related to organic micro-contaminants," Environ. Sci. Eur., vol. 32, no. 1, 2020, doi: 10.1186/s12302-019-0283-0.

[12] K. Atta et al., "Impacts of salinity stress on crop plants : improving salt tolerance through genetic and molecular dissection," no. September, pp. 1–21, 2023, doi: 10.3389/fpls.2023.1241736.

[13] W. M. Khairy, M. Bakr, and A. Ghany, "Sustainable Management of Treated Wastewater, the New El-Mahsama Wastewater Treatment Plant in Sinai," J. Environ. Treat. Tech. 2021, vol. 9, no. 4, pp. 804–814, 2021, doi: 10.47277/JETT/9(4)814.

[14] H. Myrans, J. F. Torres, M. E. Mahani, and R. M. Gleadow, "Irrigation using slightly saline water from emerging desalination technologies as a solution to short-term drought," no. July, pp. 1–12, 2024, doi: 10.1002/ppp3.10577.

[15] X. Li, C. Zhang, Z. Huo, and A. J. Adeloye, "A sustainable irrigation water management framework coupling water-salt processes simulation and uncertain optimization in an arid area," vol. 231, no. 17, p. 105994, 2020.

[16] J. Barnes, "Mixing waters: The reuse of agricultural drainage water in Egypt," Geoforum, vol. 57, pp. 181–191, 2014, doi: 10.1016/j.geoforum.2012.11.019.

[17] W. Assar, M. G. Ibrahim, W. Mahmod, and M. Fujii, "Assessing the agricultural drainage water with water quality indices in the El-Salam Canal Mega Project, Egypt," Water (Switzerland), vol. 11, no. 5, 2019, doi: 10.3390/w11051013.

[18] A. A. Agrama and A. S. Amer, "Investigation of El-Salam canal water quality, south El-Qantara sharq area," J. Appl. Sci. Res., vol. 8, no. 4, pp. 1927–1935, 2012.

[19] A. M. Raslan, P. H. Riad, and M. A. Hagras, "1D hydraulic modelling of Bahr El-Baqar new channel for northwest Sinai reclamation project, Egypt," Ain Shams Eng. J., vol. 11, no. 4, pp. 971–982, 2020, doi: 10.1016/j.asej.2020.02.005.