

Impact of modernization on drinking water quality: A case study of the El-Galaa treatment plant in Tanta, Egypt

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ABSTRACT

Aging water treatment plants in developing countries often operate beyond their design capacities, potentially compromising operational efficiency and water quality even when regulatory standards are met. This study evaluates the impact of a comprehensive modernization program (2012–2019) at the El-Galaa Water Treatment Plant in the Nile Delta, Egypt, serving approximately 180,000 inhabitants. Thirty-one paired raw and treated water samples were analyzed for key physicochemical parameters; and treatment performance was assessed using the weighted arithmetic water quality index (WAWQI). Prior to modernization, treated water exhibited a paradoxical pattern: although all individual parameters complied with regulatory limits, the integrated WQI classification indicated poor water quality (66.1 ± 19.4), largely driven by excessive alum dosing (>60 mg/L), which increased total dissolved solids and hardness. Infrastructure upgrades targeting clarification efficiency, hydraulic performance, and filtration were implemented alongside a 150% capacity expansion. Following modernization, turbidity decreased by 70.8% (0.72 ± 0.23 to 0.21 ± 0.08 NTU), and optimized alum dosing (~ 35 mg/L) reduced chemical consumption while improving integrated water quality. Consequently, the WQI classification of treated water improved from poor to excellent (22.7 ± 6.2). The findings highlight how integrated water quality metrics can reveal treatment inefficiencies that remain hidden under compliance-based monitoring and demonstrate the benefits of targeted modernization strategies for aging treatment plants.

Keywords: water treatment plant upgrade, weighted arithmetic water quality index, tube settlers, sustainable retrofitting, Egypt water infrastructure, conventional water treatment, pre-upgrade and post-upgrade assessment.

INTRODUCTION

Access to safe drinking water remains a major global challenge and is a key objective of international public health and development agendas (WHO, 2021). In many regions of the world, particularly in developing countries, potable water is supplied through surface water treatment plants constructed several decades ago, which are now approaching or exceeding their intended operational lifespan (Perera et al., 2021; Tella et al., 2025). As urban populations continue to grow and water demand increases, many of these facilities are forced to operate significantly above their original design capacities. In addition, increasing variability in raw water quality is driven by climate variability, watershed degradation, and

anthropogenic pollution, which further complicates treatment processes (Swinamer et al., 2024; Abalasei et al., 2025).

Consequently, treatment plants may formally comply with regulatory standards for individual water quality parameters while still operating under suboptimal conditions that compromise treatment efficiency and system resilience. This situation can lead to increased operational costs, higher chemical consumption, and reduced capacity to cope with sudden changes in raw water quality (Beshir et al., 2025; Mensah-Akutteh et al., 2022; Heberling et al., 2015).

The deterioration of water treatment performance has important socioeconomic and public health implications. Inadequate or inefficient water treatment can increase the risk of waterborne

diseases, place additional financial burdens on utilities, and exacerbate the vulnerability of populations that rely heavily on centralized drinking water systems (Prüss-Ustün et al., 2019; WHO/UNICEF, 2021). Furthermore, aging infrastructure often limits the capacity of treatment plants to respond effectively to environmental stressors such as seasonal fluctuations in turbidity, extreme hydrological events, or increasing pollutant loads (Delpla et al., 2009; Whitehead et al., 2009).

Consequently, evaluating the operational performance of aging treatment plants and identifying effective modernization strategies is a critical research priority for ensuring sustainable and reliable drinking water supply systems.

In Egypt, the majority of drinking water treatment facilities rely on surface water derived from branches of the Nile River, particularly within the Nile Delta region. These systems are characterized by pronounced seasonal variability in raw water quality, including fluctuations in turbidity (17–80 cm transparency), total dissolved solids (344–752 mg/L), and nutrient concentrations, which can impose operational challenges on treatment processes, including coagulation, clarification, and filtration efficiency (Ezzat et al., 2017; Azzam et al., 2022; Ashmawy, 2016). The Rosetta Branch of the Nile, which supplies several treatment plants in the delta region, receives substantial agricultural, industrial, and domestic discharges. As a result, the river frequently exhibits elevated organic pollutant loads, with biochemical oxygen demand (BOD) concentrations reported in the range of 5.34–35 mg/L in the Rosetta Branch's raw water (El-Sayed et al., 2020; Abdel-Satar et al., 2017; Goher et al., 2014). These conditions increase the operational complexity of drinking water treatment plants and may necessitate higher coagulant dosages and more intensive treatment processes to maintain regulatory compliance.

Water quality index (WQI) approaches have been widely applied as integrative tools for assessing water quality, as they combine multiple physicochemical parameters into a single interpretable metric (Tyagi et al., 2013; Gupta and Gupta, 2021). Among these approaches, the weighted arithmetic water quality index (WAWQI) method – operationalized in the present study following the formulation of Ayoub (2017) – has gained popularity due to its transparent structure, ease of application, and ability to incorporate multiple water quality indicators into a composite evaluation of overall water status.

Unlike assessments based solely on compliance with individual regulatory thresholds, WQI-based approaches allow the cumulative effects of multiple parameters to be evaluated simultaneously, including their interactions with treatment chemistry (Oliveira et al., 2019; Beshir et al., 2025). This proves particularly useful for identifying systemic inefficiencies in water treatment processes that may remain undetected when parameters are considered independently. However, despite the increasing use of WQI methods in water quality assessment, relatively few studies have applied these approaches to evaluate the operational performance of drinking water treatment plants before and after major infrastructure upgrades. Existing applications have largely focused on surface water monitoring (Gabr and Soussa, 2023; Abdou et al., 2026), treatment plant efficiency assessment under stable operating conditions (Alver, 2019; Beshir et al., 2025), or methodological reviews (Uddin et al., 2021; Kachroud et al., 2019). In particular, empirical studies utilizing integrated water quality indices to assess modernization outcomes in aging treatment facilities in developing countries, including Egypt, are lacking.

Addressing this gap is essential for improving the understanding of how infrastructure modernization influences both operational efficiency and integrated water quality outcomes in aging treatment systems. In particular, it remains insufficiently understood whether treatment plants that formally meet regulatory standards may still exhibit hidden performance limitations that become evident when evaluated using integrated water quality metrics.

Unlike previous studies that primarily apply water quality indices as descriptive tools, this study integrates WAWQI within a controlled pre- and post-upgrade comparative framework using consistent sampling protocols and operational conditions. This approach enables the identification of discrepancies between regulatory compliance and overall water quality, and links these discrepancies directly to specific operational practices, particularly coagulant overdosing. In addition, the study provides one of the few documented evaluations of large-scale retrofitting of a conventional water treatment plant in the Egyptian context, combining process-level analysis with integrated performance assessment. The findings therefore contribute not only to case-specific understanding but also to the broader application of water quality indices as

diagnostic tools for process optimization in aging treatment infrastructure.

The present study investigates the operational performance of the El-Galaa Water Treatment Plant in Tanta, Egypt, before and after a comprehensive modernization program implemented between 2012 and 2019. The study is based on the hypothesis that compliance with individual regulatory parameters may not fully reflect the integrated quality of treated water and that modernization measures targeting hydraulic performance, clarification efficiency, and chemical dosing optimization can significantly improve overall water quality when assessed using integrated indices.

Through this analysis, the study aims to provide new empirical evidence on the role of integrated water quality assessment in diagnosing hidden inefficiencies in aging drinking water treatment infrastructure and to inform modernization strategies for similar facilities operating under comparable environmental and operational conditions.

MATERIALS AND METHODS

The El-Galaa water treatment plant (WTP) is a conventional surface water treatment facility located in Tanta City (30.7796° N, 31.2668° E), Gharbia Governorate, in the Nile Delta region of Egypt. Raw water is abstracted from the El-Qassid Canal, which forms part of the irrigation and drainage network supplying water across the Delta region. Prior to the recent modernization program, the plant had a nominal design capacity of 240 L s⁻¹

(approximately 20.7 million m³ year⁻¹), although operational records indicate that actual hydraulic loading during peak seasonal demand frequently exceeded this design capacity by 15–20% and supplied drinking water to an estimated population of approximately 180,000 inhabitants. The plant was originally commissioned in 1924; the plant had not undergone any major structural refurbishment prior to the 2019 modernization program, representing approximately 95 years of near-continuous operation. The plant operates using a conventional treatment train consisting of coagulation, flocculation, clarification, rapid sand filtration, and chlorination (Crittenden et al., 2012).

Plant layout and site photographs – before upgrading

Figure 1 presents an aerial satellite image of the El-Galaa WTP prior to the modernization program, acquired from Google Earth (image acquisition: May 2011, © Maxar Technologies), while Figure 2 illustrates the plant layout in its original configuration (2012). The treatment facility consisted of seven circular clari-flocculation units, six circular rapid sand filters, two ground-level treated water storage reservoirs, a low-lift pumping station, and auxiliary operational buildings.

Figure 3 presents a representative clari-flocculation unit prior to upgrading. Visible sludge accumulation along the basin perimeter and the absence of mechanical flocculation equipment contributed to reduced hydraulic retention time and clarification inefficiency. Figure 4 shows the



Figure 1. Aerial satellite image of El-Galaa WTP prior to the modernization program, Tanta City, Egypt. Image source: Google Earth

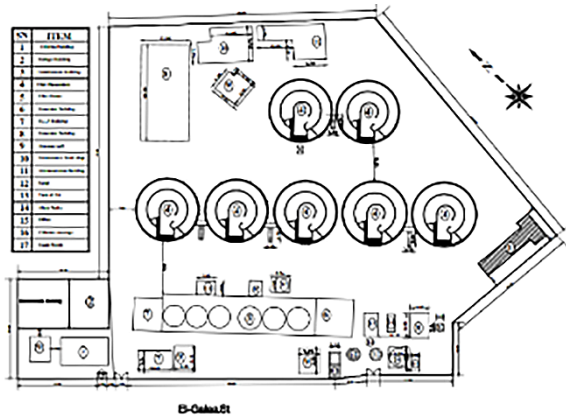


Figure 2. layout of El-Galaa water treatment plant before upgrading (2012), showing the seven existing clari-flocculation units, six rapid sand filters, and storage units, and auxiliary infrastructure



Figure 3. Representative clari-flocculation unit prior to upgrading, showing the central flocculation zone and surrounding settling annulus

rapid sand filter building prior to rehabilitation, illustrating the six circular metallic filter vessels originally commissioned in the early twentieth century and operated for decades without major structural refurbishment. The deteriorated condition of the units is directly observable in the photograph: visible surface corrosion is apparent on the upper flanges and outer surfaces of the filter vessels, while the absence of dedicated backwash pumping infrastructure and automated backwash control systems – evident from the lack of pump housings and instrumentation in the background – necessitated manual high-pressure washing and contributed to inconsistent filter performance and reduced operational reliability.



Figure 4. Rapid sand filter building prior to rehabilitation, showing the six circular metallic filter vessels originally commissioned in the early twentieth century. The deteriorated condition of the units is evident from visible surface corrosion on the filter vessels and the absence of dedicated backwash pumping infrastructure, reflecting decades of near-continuous operation without major structural refurbishment

Pre-upgrade treatment process configuration

Raw water intake structure

Raw water abstraction was performed through a masonry intake structure located adjacent to the El-Qassid Canal. The intake structure was positioned at the canal bank, with the suction inlet established at an invert elevation of -8.00 m relative to the local benchmark, corresponding to approximately 6.65 m below the canal bed elevation. The typical raw water abstract depth varied seasonally with irrigation rotation schedules and prevailing hydrological conditions. The intake system conveyed raw water via a $\text{Ø } 1.90$ m reinforced concrete suction pipeline to four centrifugal pumps, each with a nominal capacity of $150 \text{ L}\cdot\text{s}^{-1}$, with two units active and two on standby under normal operation. Full hydraulic and structural parameters are documented in the as-built engineering drawings issued by the Gharbia Water and Wastewater Company (2018) and presented in Appendix I.

Several operational limitations were identified in the intake system. These included frequent blockage of the bar screen during high-flow periods, sediment accumulation within the suction pipeline attributable to the sub-bed intake

position, hydraulic instability when multiple pumping units were operated simultaneously, and insufficient conveyance capacity to accommodate projected increases in water demand. No dedicated pre-treatment or flow equalization facilities were installed upstream of the treatment process (APHA-AWWA-WEF, 2017).

These limitations were identified as key drivers for the rehabilitation of the raw water intake system and associated rising mains during the modernization program.

In-line rapid mixing system

Coagulation was achieved through in-line alum dosing upstream of the clarification units. Prior to the 2019 upgrade, liquid aluminium sulphate ($Al_2(SO_4)_3$), supplied by the Egyptian Alum Company (ASCE), was stored in elevated galvanized steel tanks and delivered into the raw water main by gravity feed, without mechanical dosing pumps, automated control systems, or dedicated rapid-mixing equipment. A purpose-built dilution basin allowed operators to prepare the alum solution at a pre-calculated concentration. The draw-off flow rate was monitored by a float-type flowmeter (rotameter) installed on the storage tank outlet line. All dosage adjustments were performed manually by operators based on visual turbidity assessment of the raw water intake.

Operational records for 2018 ($n = 31$ measurement points) confirm that the applied dose ranged from 42 to 55 mg/L (annual mean: 46.7 mg/L), with the highest values recorded during the spring flood season along the El-Qassid Canal (March mean: 51.3 mg/L applied; 59.0 mg/L actual). Critically, the actual measured dose exceeded the applied target in all 31 records, with a mean overdose of +6.7 mg/L (+14.3%) and a maximum of +13.0 mg/L (+27.1%). Consequently, the actual delivered dose ranged from 44.9 to 63.3 mg/L (annual mean: 54.0 mg/L); the peak actual dose of 63.3 mg/L constitutes the quantitative basis for the >60 mg/L figure cited in the abstract. This systematic overdosing is a characteristic failure mode of manual gravity-fed systems, in which operators compensate for inadequate mixing energy by increasing the coagulant dose rather than by enhancing mixing intensity.

Since rapid mixing was achieved solely through the hydraulic turbulence of the flowing raw water, the system lacked any independent means of regulating mixing intensity (G-value / Camp number) or hydraulic residence time (HRT). Under elevated

turbidity conditions, insufficient turbulent energy resulted in incomplete charge neutralization and poor micro floc aggregation, which in turn required further dose escalation, culminating in excess aluminium hydroxide sludge generation. Field observations conducted during this study (March 2026) confirmed significant sludge accumulation around the base of the alum storage tanks (Figure G.4, Appendix G), providing direct visual corroboration of the quantitative overdosing pattern documented in the operational records. This finding is consistent with published evidence indicating that uncontrolled gravity-fed coagulation systems are particularly susceptible to coagulant overdosing and elevated sludge yields under variable raw water quality (Crittenden et al., 2012).

Clarification units

The plant was equipped with seven circular Clari-floculators, each with an outer diameter of 20.00 m, a side water depth (SWD) of 4.90 m, and a nominal treatment capacity of approximately 40 L s^{-1} , corresponding to a theoretical hydraulic retention time (HRT) of approximately 10.2 hours per unit and a theoretical total clarification capacity of approximately 280 L s^{-1} . In practice, the effective plant throughput was constrained by hydraulic limitations in downstream treatment units. Operational challenges were observed in the sludge management system. Sludge removal was performed irregularly, resulting in excessive sludge accumulation within the clarifiers. This accumulation reduced the effective basin volume, shortened the HRT, and thereby decreased clarification efficiency, limiting the plant's overall hydraulic capacity.

Filtration units

Filtration was carried out using six circular rapid gravity sand filters, each with an internal diameter of 6.0 m and a unit surface area of 28.3 m^2 , giving a total active filtration area of 169.6 m^2 . Each filter operated at a nominal capacity of 30–35 L/s (APHA-AWWA-WEF, 2017), corresponding to a pre-upgrade rate of filtration (ROF) of 12.72 m/h. The filter media comprised a uniform sand layer (effective grain size: 0.75–1.40 mm; depth: 70 cm) underlain by four graded gravel support layers totaling 40 cm depth, giving a total filter bed depth of 110 cm. The main operational drawbacks included manual backwashing driven by high-pressure water jets, structural corrosion

of filter vessels, the absence of dedicated backwash pumps and automated flow control, and recirculation of backwash waste into the drainage system without further treatment. Full hydraulic calculations and filter medium specifications are provided in Appendix A.

Disinfection and storage

Disinfection of treated water was achieved through chlorination using liquefied chlorine gas (Cl₂) stored in pressurized one-tonne steel cylinders, injected into the filtered water stream using a fixed-rate gas chlorinator with manual dosage adjustment. The applied chlorine dose ranged from 5.0 to 5.5 mg/L, yielding a mean residual chlorine concentration of 2.05 ± 0.34 mg/L in the treated effluent, within the Egyptian regulatory range of 0.5–5.0 mg/L. Residual chlorine was measured at all sampling points using the DPD colorimetric method (APHA Method 4500-Cl G).

Following disinfection, treated water was stored in two ground-level reservoirs, each measuring approximately 15 × 30 × 4 m, with a combined storage capacity of approximately 3,600 m³. At the nominal design flow rate, this storage volume provided an emergency buffer of approximately three hours of production, corresponding to approximately 14% of the plant’s daily treated water output. Full documentation of the chlorination system, including CT values and field photographs, is provided in Appendix C. The major operational limitations of the treatment system prior to modernization are summarized in Table 1.

Pre-upgrade operational constraints and performance limitations

Prior to the modernization program, multiple structural and operational deficiencies were identified across the main treatment stages of the El-Galaa Water Treatment Plant. These deficiencies collectively constrained the plant’s hydraulic capacity, increased chemical consumption, and reduced overall treatment performance.

Operational limitations were observed in the raw water intake, coagulation and mixing processes, clarification efficiency, filtration performance, and sludge management. In particular, the absence of controlled rapid mixing, irregular sludge removal from clarification units, and limitations in the filtration backwash system contributed to reduced treatment efficiency under variable raw water conditions. These deficiencies were systematically identified through engineering inspection reports, routine operational monitoring records, and plant performance logs maintained by the Gharbia Water and Wastewater Company over the period 2012–2018, prior to the initiation of the upgrading program.

A structured summary of the main design characteristics of the treatment units and their associated operational challenges prior to modernization is presented in Table 1.

Upgrading and rehabilitation program (2012 to 2019)

In response to the identified operational constraints and capacity deficiencies – notably that

Table 1. Summary of existing treatment units and operational constraints at El-Galaa Water Treatment Plant before upgrading

| Treatment unit | Specifications | Design capacity | Key operational issues |
|------------------------------|---|----------------------|--|
| Intake structure | 4 pumps × 150 L/s; brick-masonry conduit | 300 L/s (effective) | Frequent clogging; sediment accumulation; poor screens |
| In-line mixing | Alum injection into pipeline; no mechanical mixer | — | Limited mixing control during peak turbidity events |
| Clari-flocculators (7 units) | 20 m diameter; 4.9 m depth; 40 L/s each | 280 L/s total | Reduced HRT due to sludge accumulation; low surface overflow rates; irregular sludge withdrawal (intervals up to 6 months) |
| Rapid sand filters (6 units) | 6 m diameter; manual backwashing | ~210 L/s total | Manual operation; structural corrosion; no backwash pump |
| Ground storage | 15 × 30 × 4 m (2 tanks) | 3.600 m ³ | Limited emergency storage; <3 hours backup capacity |
| Overall limitations | — | 240 L/s effective | High alum consumption (>60 mg/L); excessive sludge generation; chemical inefficiency |

Note: Gharbia Water and Wastewater Company, engineering inspection reports and routine operational monitoring records (2012–2018), compiled prior to project initiation.

the pre-upgrade plant was operating at 15–20% above its nominal design capacity of 240 L/s during peak demand seasons – a comprehensive upgrading program was implemented between 2012 and 2019 with the following objectives: (1) expand treatment capacity from 240 L/s to 600 L/s (a 150% expansion); (2) modernize all treatment units by integrating current technology; (3) reduce chemical consumption and sludge production; (4) maximize operational reliability and resilience to raw water quality fluctuations; and (5) ensure long-term compliance with Egyptian drinking water standards and WHO Guidelines for Drinking-Water Quality. The upgraded and new treatment units are discussed in Table 2.

Key upgrading interventions comprised: (i) intake rehabilitation, including new primary screening and improved conveyance pipework; (ii) replacement of raw water pipelines with modern reinforced concrete pipelines (diameter 1,200 mm; total length 1,000 m); (iii) retrofitting of three of the existing clari-flocculators with PVC tube settlers inclined at 55–60° — of the original seven clari-flocculators, three units were decommissioned, three were retrofitted, and one is retained in standby for a subsequent upgrading phase; (iv) construction of eight new automated rapid sand filters (6 × 8 m each) with a dedicated backwash pump station; (v) construction of a new ground-level storage reservoir (36 × 32 m); and (vi) installation of a new high-lift pump station equipped with variable-speed drives for efficient distribution control. Coagulation optimization was a central component of the upgrading program. The gravity-fed manual dosing system was replaced with a JESCO (Germany) membrane metering pump system equipped with automated flow-proportional control, enabling real-time adjustment of the alum dose in response to raw water flow rate and turbidity. The coagulant type remained liquid aluminium sulphate ($Al_2(SO_4)_3$) supplied by the Egyptian Alum Company (ASCE); consequently, the new system eliminated the overdosing characteristic of the pre-upgrade gravity-fed arrangement, significantly optimizing coagulant use. Post-upgrade operational records (2019) confirm a reduced alum dose of 30–40 mg/L (annual mean: approximately 35 mg/L). This represents an 18–22% reduction compared to the pre-upgrade mean of 46.7 mg/L. Full documentation of the upgraded coagulation dosing system, including pump specifications, calibration records, and field photographs, is provided in Appendix G.

Plant layout and site photographs – after upgrading

Following completion of the modernization program in 2019, the treatment plant was substantially reconfigured. The updated plant layout is illustrated in Figure 5, which highlights three principal changes: (i) the replacement of seven original circular clari-flocculators with three retrofitted units equipped with tube settlers, (ii) the addition of a new 8-filter rapid sand filtration building, and (iii) the construction of a new ground-level storage reservoir and high-lift pump station. These spatial changes directly address the pre-upgrade hydraulic bottlenecks and capacity deficit documented in Table 1.

Figures 6 and 7 present engineering drawings of the upgraded clari-flocculation units equipped with tube settlers, including a cross-sectional view (Section A–A) showing the tube settler configuration. In Figure 6, the arrangement of inclined tube settler modules within the settling zone should be noted alongside the positioning of the mechanical flocculator paddles at the basin inlet — a configuration that eliminates the uncontrolled flocculation characteristic of the pre-upgrade system. Figure 7 (Section A–A) illustrates the 55–60° inclination of the tube settlers relative to the horizontal; this geometry is the principal hydraulic modification responsible for the surface overflow rate reduction and enhanced solids removal efficiency reported in Table 2.

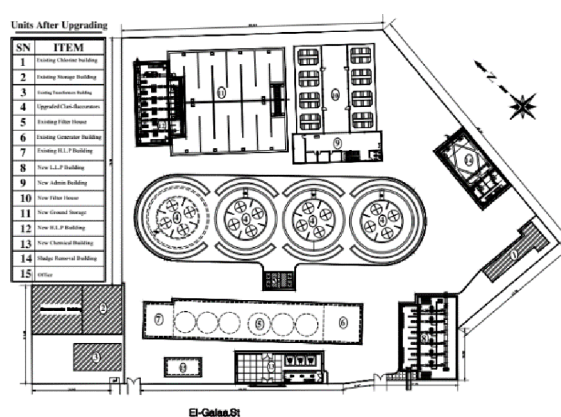


Figure 5. Post-upgrade layout of El-Galaa Water Treatment Plant (2019), showing 3 retrofitted clari-flocculators with tube settlers (center), a new 8-unit rapid sand filtration building (upper right), and a new ground storage reservoir with high-lift pump station (upper left). Source: Gharbia Water and Wastewater Company, as-built engineering drawings (Appendix J, Figure J-1)

Table 2. Summary of upgraded and new treatment units at El-Galaa Water Treatment Plant after 2019 commissioning

| Treatment unit | Quantity | Specifications | Capacity | Key improvements |
|--|-----------------|---|--|---|
| Upgraded clari-flocculators | 3 of 7 existing | 20 m diameter; PVC tube settlers (55–60°); 6 m depth | 220 L/s each (660 L/s total) | 340% capacity increase per unit; enhanced settling |
| New rapid sand filters | 8 units | 6 × 8 m footprint; automatic backwash system | 75 L/s each (600 L/s total) | Fully automated; modular design; efficient backwash |
| New intake structure | 1 system | Ø 1200 mm concrete pipeline; L = 1000 m; gravity fed | 600 L/s | Improved screening; reduced sediment accumulation |
| Mechanical flocculators | 12 units | Vertical paddle wheels; gentle mixing ($G \approx 10\text{--}20\text{ s}^{-1}$) | — | Optimized flocculation control; uniform aggregate formation |
| New ground storage | 1 reservoir | 36 × 32 m footprint; reinforced concrete | ~11,557 m ³ | 70-hour coverage at peak flow; emergency buffer capacity |
| New high-lift pump station | 1 unit | Variable-speed centrifugal pumps; VFD control | 600 L/s | Energy-efficient; flow modulation; pressure regulation |
| Alum dosing and coagulation control system | 1 system | JESCO (Germany) membrane metering pumps; flow-proportional automated control; liquid Al ₂ (SO ₄) ₃ supplied by Egyptian Alum Company (ASCE); pre-upgrade gravity-fed manual system replaced | Pre: 42–55 mg/L (mean 46.7 mg/L); Post: 30–40 mg/L (mean ~35 mg/L) | Elimination of systematic overdosing; 18–22% reduction in alum consumption; automated real-time dose adjustment; full documentation in Appendix G |
| Overall capacity | — | — | 600 L/s | 150% capacity increase; modernized infrastructure; enhanced efficiency |

Note: Gharbia Water and Wastewater Company, Final Completion Certificate No. 41 (December 2025) and project design documentation; capacity figures derived from as-built engineering drawings. Supporting engineering drawings are reproduced in Appendix J (Figures J-1 to J-33) (Gharbia Water and Wastewater Company, 2020). Unit specifications and capacity values have been independently verified against the as-built drawings; alum dosing system parameters are further documented in Appendix G (operational records, pump specifications, and field photographs).

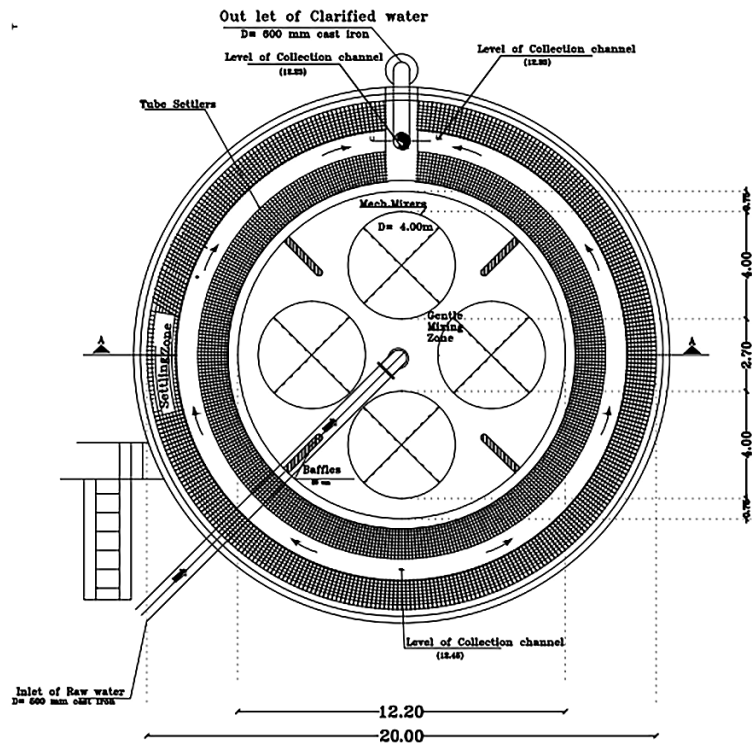


Figure 6. Engineering plan of the upgraded clari-flocculator (post-2019). This figure illustrates the spatial arrangement of PVC inclined tube settler modules within the settling zone (shaded area), the placement of 4 vertical-paddle mechanical flocculators at the basin inlet, and the inlet/outlet weir configuration. This layout replaces the pre-upgrade uncontrolled gravity-fed flocculation with a defined, hydraulically controlled treatment sequence. Source: Gharbia Water and Wastewater Company, design drawings (Appendix J, Figure J-7)

Figure 8 shows a photograph of the upgraded clarification unit following completion of the rehabilitation works in 2019, showing the structural rehabilitation of the basin interior and the orderly arrangement of the PVC tube modules. This contrasts directly with the deteriorated pre-upgrade condition documented in Appendix B.

Sampling program

To evaluate treatment performance before and after modernization, the study compared operational conditions during two monitoring periods: a pre-upgrade period (2018) and a post-upgrade period (2019). Identical sampling protocols, analytical methods, and quality assurance procedures were applied during both monitoring periods in order to ensure comparability of the datasets. Each monitoring period covered a full twelve-month cycle (January–December). A total of thirty-one paired raw and treated water samples were collected during each period: twenty-four obtained at strict biweekly intervals, and six additional samples collected during peak turbidity events associated with seasonal agricultural runoff and increased sediment transport in the Nile Delta. Sampling locations included: (a) raw water sampled downstream of the intake pumping station; and (b) treated water sampled after disinfection and prior to entry into the storage reservoirs. A schematic diagram of the sampling points is provided in Appendix D. All samples were collected in sterile sampling bottles and transported to the plant laboratory in insulated coolers maintained at approximately 4°C.



Figure 8. Field photograph of the completed tube settler installation within the upgraded clari-flocculator (post-2019 commissioning). The orderly arrangement of PVC inclined tube modules is visible across the full settling zone, confirming installation conformity with the design geometry shown in Figures 6 and 7. The rehabilitated internal structure – including repaired concrete surfaces and new inlet weirs – contrasts with the deteriorated pre-upgrade condition and directly corroborates the structural improvements listed in Table 2. Source: Field photograph from El-Galaa Water Treatment Plant site visit after upgrading works (2019)

Field parameters including temperature, pH, and dissolved oxygen were measured in situ using a calibrated HACH HQ430d Flexi multiparameter meter (HACH, USA; S/N: 210700040050), with weekly electrode calibration. Total dissolved solids and temperature were additionally verified

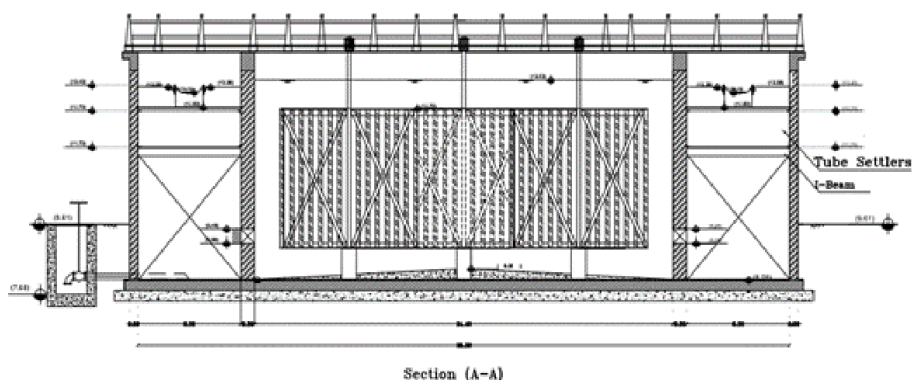


Figure 7. Section A–A through the upgraded clari-flocculator, showing the installation geometry of the inclined tube settler modules within the clarification zone. The 55–60° inclination of the PVC tubes relative to horizontal is the critical hydraulic parameter responsible for the enhanced surface overflow rate and improved solids removal efficiency. This cross-section also illustrates the increased effective water depth achieved by the retrofit compared to the original open-basin configuration. Source: Gharbia Water and Wastewater Company, design drawings (Appendix J, Figure J-8)

using an ADWA AD8000 conductivity/TDS meter (ADWA, Hungary; S/N: H004310007).

Analytical methods

Physicochemical parameters were analyzed in accordance with the Standard Methods for the Examination of Water and Wastewater, 23rd edition (APHA-AWWA-WEF, 2017), at the laboratory of El-Galaa Water Treatment Plant (Gharbia Water and Wastewater Company). The parameters analyzed included: turbidity, pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), total alkalinity, total hardness, calcium hardness, magnesium hardness, chloride, sulfate, iron, manganese, ammonia, nitrite, nitrate, and residual chlorine.

Turbidity was measured using a HACH TL2300 laboratory turbidimeter (HACH, USA; S/N: 2019080C0117; detection limit: 0.01 NTU), calibrated monthly using HACH StabCal primary standards. pH and dissolved oxygen were determined using a HACH HQ430d Flexi multiparameter meter (HACH, USA; S/N: 210700040050; detection limit: ± 0.01 pH units), with weekly electrode calibration. EC and TDS were measured using an ADWA AD8000 conductivity/TDS meter (ADWA, Hungary; S/N: H004310007; detection limit: 1 $\mu\text{S}/\text{cm}$ and 1 mg/L respectively). Iron, manganese, ammonia, nitrite, and nitrate were determined by colorimetric and UV spectrophotometric methods using a HACH DR6000 UV-Vis's spectrophotometer (HACH, USA; S/N: 2362072; calibration $R^2 \geq 0.995$). Total hardness, alkalinity, chloride, and sulfate were determined by titrimetric and turbidimetric methods as specified in APHA-AWWA-WEF (2017). Residual chlorine was measured by the DPD colorimetric method (APHA Method 4500-Cl G). Full instrument specifications, serial numbers, and calibration records are provided in Appendix E. A complete summary of all analytical methods, instruments, APHA-AWWA-WEF (2017) Standard Method codes, detection limits, and the parameters used in the WAWQI calculation is presented in Table 3.

Quality control procedures — including method blanks and duplicate analyses ($\geq 10\%$ of samples) — were applied to every analytical batch to ensure accuracy and precision. Measurements below the instrument detection limit are reported as “< LOD” and assigned a value of zero for WQI calculation.

Water quality index methodology

The WAWQI method, as described by Ayoub (2017) following Oni and Fasakin (2016) and Gupta and Gupta (2021), was adopted to produce a single composite index of treated water quality. This approach assigns parameter weights inversely proportional to their permissible standard values, ensuring that parameters with stricter standards (lower S_n) receive higher relative weight in the index. Unit weights (W_n) are calculated as

$$W_n = K/S_n \quad (1)$$

where: S_n is the WHO (2011) standard permissible value of the n^{th} parameter and $K = 1/\sum(1/S_n)$ is a proportionality constant ensuring.

$$\sum W_n = 1 \quad (2)$$

Standard values comply with WHO (2011) Guidelines for Drinking-Water Quality as applied by Ayoub (2017) for Egyptian surface-water treatment plants; Egyptian national standards were cross-referenced and found consistent with these values for all ten parameters included in the index. The complete parameter weights, standard values, ideal values, and weight multipliers are presented in Table 4 ($K = 0.821993$; $\sum W_n = 1.000$). The raw WAWQI calculation data for all 31 samples per monitoring period, including per-parameter sub-index values and the full Excel calculation dataset, are provided in Appendix D.

The WAWQI was selected over alternative WQI formulations — including the entropy-weight WQI and the Canadian Council of Ministers of the Environment (CCME) WQI — for three reasons: (a) its transparent, reproducible weighting structure does not require entropy calculations or subjective expert elicitation, making it directly applicable in operational plant monitoring contexts; (b) it has been applied in previous drinking water quality studies in Egypt and the Nile Delta region (Ayoub, 2017; Azzam et al., 2022), providing a directly comparable methodological basis; and (c) its standard permissible values are consistent with the WHO (2011) Guidelines for Drinking-Water Quality as applied by the Gharbia Water and Wastewater Company. The quality rating (qn) for each parameter is given by

$$qn = [(V_n - Vid)/(S_n - Vid)] \times 100 \quad (3)$$

Table 3. Analytical methods, instruments, and standard methods references (APHA-AWWA-WEF, 2017) for all physicochemical parameters analyzed in this study

| Parameter | Unit | Instrument / Method | APHA-AWWA-WEF (2017) method code | Detection limit | Used in WAWQI |
|-------------------------------|------------------------|--|--|-----------------|---------------|
| Turbidity | NTU | HACH TL2300 turbidimeter | SM 2130B (Nephelometric Method) | 0.01 NTU | Yes (Sn=1) |
| pH | — | HACH HQ430d Flexi pH meter | SM 4500-H ⁺ B (Electrometric Method) | ±0.01 units | Yes (Sn=8) |
| Total Hardness | mg/L CaCO ₃ | EDTA titrimetric method | SM 2340C (EDTA Titrimetric Method) | 2 mg/L | Yes (Sn=300) |
| Total Alkalinity | mg/L CaCO ₃ | Acid titrimetric method (H ₂ SO ₄ 0.02N) | SM 2320B (Titrimetric Method — acid titration) | 2 mg/L | Yes (Sn=120) |
| TDS | mg/L | ADWA AD8000 conductivity/TDS meter | SM 2540C (Total Dissolved Solids) | 1 mg/L | Yes (Sn=500) |
| Ca ²⁺ (as ion) | mg/L | Derived from Calcium Hardness (SM 3500-Ca) | SM 3500-Ca B → ion conversion | See CaH | Yes (Sn=75) |
| Mg ²⁺ (as ion) | mg/L | Derived from Magnesium Hardness (SM 3500-Mg) | SM 3500-Mg B → ion conversion | See MgH | Yes (Sn=30) |
| Cl ⁻ | mg/L | Argentometric / ion chromatography | SM 4500-Cl ⁻ B (Argentometric Method) | 1 mg/L | Yes (Sn=250) |
| SO ₄ ²⁻ | mg/L | Turbidimetric method | SM 4500-SO ₄ ²⁻ E (Turbidimetric Method) | 1 mg/L | Yes (Sn=200) |
| NO ₃ ⁻ | mg/L | HACH DR6000 UV spectrophotometry | SM 4500-NO ₃ ⁻ B (UV Spectrophotometric) | 0.1 mg/L | Yes (Sn=45) |
| EC | µS/cm | ADWA AD8000 conductivity meter | SM 2510B (Electrical Conductivity) | 1 µS/cm | No |
| Fe (total) | mg/L | HACH DR6000 Colorimetric (FerroVer method) | SM 3120B (Colorimetric Method) — FerroVer, λ = 510 nm | 0.01 mg/L | No |
| Mn | mg/L | HACH DR6000 Colorimetric (Persulfate method, λ = 525 nm) | SM 4500-Mn B (Persulfate method, λ = 525 nm) | 0.01 mg/L | No |
| NH ₃ | mg/L | HACH DR6000 Nessler method | SM 4500-NH ₃ C (Nesslerization Method) | 0.02 mg/L | No |
| NO ₂ ⁻ | mg/L | HACH DR6000 colorimetric | SM 4500-NO ₂ ⁻ B (Colorimetric Method) | 0.01 mg/L | No |
| Residual Cl ₂ | mg/L | DPD colorimetric (HACH photometer) | SM 4500-Cl G (DPD Colorimetric Method) | 0.02 mg/L | No |
| Temperature | °C | HACH HQ430d / ADWAAD8000 | SM 2550B (Temperature) | ±0.1 °C | No |

DPD = N,N-diethyl-p-phenylenediamine; SM = Standard Methods (APHA-AWWA-WEF, 2017, 23rd ed.); Sn = WHO (2011) permissible standard. All colorimetric analyses performed on HACH DR6000 UV-Vis spectrophotometer. Ca²⁺ and Mg²⁺ ionic concentrations derived from Calcium Hardness and Magnesium Hardness measurements: Ca²⁺ = CaH × (40.08/100.09); Mg²⁺ = MgH × (24.305/100.09).

where: V_n is the measured concentration, V_{id} is the ideal value in pure water ($V_{id} = 0$ for all parameters except pH, for which $V_{id} = 7.0$), and S_n is the permissible standard.

Water quality is classified as: excellent (wqi 0–25), good (26–50), poor (51–75), very poor (76–100), or unsuitable for drinking (>100) (Oni and Fasakin, 2016; Gupta and Gupta, 2021).

The present revision adopts the WAWQI formulation of Ayoub (2017) in place of the Tyagi et al. (2013) approach referenced in the initial submission. This modification aligns the weighting scheme with WHO (2011) standard permissible values applicable to Egyptian surface-water treatment plants. The parameters, standard values, ideal values, unit weights, and WQI multipliers are presented in Table 4.

Table 4. WAWQI parameters, standard permissible values (Sn), ideal values (Vid), unit weights (Wn = K/Sn), and weight multipliers (Wn × 1000) used in the present study (K = 0.821993; ΣWn = 1.000). Standards comply with WHO (2011) guidelines (Ayoub, 2017)

| Parameter | Sn (WHO 2011) | Vid | K | Wn = K/Sn | Wn × 1000 |
|--|---------------|-----|----------|-----------|-----------|
| Turbidity | 1 | 0 | 0.821993 | 0.821993 | 821.993 |
| pH | 8 | 7.0 | 0.821993 | 0.102749 | 102.749 |
| Total Hardness (mg/L CaCO ₃) | 300 | 0 | 0.821993 | 0.002740 | 2.740 |
| Total alkalinity | 120 | 0 | 0.821993 | 0.006850 | 6.850 |
| TDS | 500 | 0 | 0.821993 | 0.001644 | 1.644 |
| Ca ²⁺ | 75 | 0 | 0.821993 | 0.010960 | 10.960 |
| Mg ²⁺ | 30 | 0 | 0.821993 | 0.027400 | 27.400 |
| Cl ⁻ | 250 | 0 | 0.821993 | 0.003288 | 3.288 |
| SO ₄ ²⁻ | 200 | 0 | 0.821993 | 0.004110 | 4.110 |
| NO ₃ ⁻ | 45 | 0 | 0.821993 | 0.018267 | 18.267 |
| Σ(1/Sn) = 1.216556 K = 0.821993 ΣWn = 1.000000 | | | | | |

Statistical analysis

All measurements are reported as mean ± standard deviation (n = 31 for each period). The differences between pre- and post-upgrade conditions were investigated using the two-sample Welch t-test (two-tailed, α = 0.05), which does not assume equal variances between the compared groups. Effect sizes were calculated using Cohen’s d to quantify the magnitude of observed differences. Standard thresholds were used to interpret effect sizes as small (>0.20), medium (>0.50), and large (>0.80). Statistical analyses were performed using Microsoft Excel (Microsoft 365, Microsoft Corporation, Redmond, WA, USA) with the Analysis ToolPak add-in. The T.TEST () function (type = 3, Welch unequal-variance, two-tailed) was applied for all pairwise comparisons; Cohen’s d was calculated using the pooled standard deviation formula. Full statistical outputs – including per-parameter t-statistics, Welch degrees of freedom, two-tailed p-values, and Cohen’s d effect sizes for all 10 water quality parameters and the composite WAWQI – are provided in Appendix K. Raw data tables and WAWQI calculation worksheets are also provided in Appendix K.

RESULTS AND DISCUSSION

Raw water quality characterization (pre-upgrade period, 2018)

All numerical values reported in this section are fully supported by primary measurement

records, raw data tables (Appendix D), step-by-step WAWQI calculation worksheets (Appendix K), and complete statistical outputs – Welch t-test, degrees of freedom, p-values, and Cohen’s d (Appendix K; Appendix L). Water samples collected from El-Qassid Canal during 2018 exhibited pronounced seasonal variability, reflecting the characteristic agricultural and hydrological forcing factors of Nile Delta irrigation canals. A comprehensive statistical summary of raw water quality parameters is provided in Table 5.

Turbidity

Raw water turbidity showed considerable variability, with values ranging from 6.5 to 25.0 NTU and a mean of 11.45 ± 3.79 NTU. These values considerably exceeded the WHO and Egyptian drinking water turbidity limit of 5 NTU applicable to treated water, confirming the need for effective coagulation-sedimentation treatment, especially during periods of increased agricultural discharge and heavier precipitation (Abbas et al., 2025).

pH and alkalinity

Raw water pH remained stable throughout the monitoring period, ranging between 7.44 and 7.82 (mean: 7.61 ± 0.10). Total alkalinity averaged 143 ± 8 mg/L as calcium carbonate, exhibiting moderate buffering capacity. These conditions are favorable for alum coagulation (optimum pH for alum: approximately 6.5 to 7.5) and reduce the need for excessive pH adjustment chemicals.

Table 5. Statistical summary of raw water quality parameters (before upgrading, n = 31)

| Parameter | Unit | Mean \pm SD | Min | Max | Egyptian Std. | WHO |
|---|------------------------|-------------------|-------|------|---------------|---------|
| Turbidity | NTU | 11.45 \pm 3.79 | 6.5 | 25.0 | 5 | 5 |
| pH | — | 7.61 \pm 0.10 | 7.44 | 7.82 | 6.5–8.5 | 6.5–8.5 |
| Temperature | °C | 24.8 \pm 4.9 | 16.4 | 31.8 | — | — |
| EC | μ S/cm | 421 \pm 62 | 333 | 557 | — | — |
| TDS | mg/L | 222 \pm 33 | 176 | 295 | 1000 | 1000 |
| Total alkalinity | mg/L CaCO ₃ | 143 \pm 8 | 128 | 165 | — | — |
| Total hardness | mg/L CaCO ₃ | 157.7 \pm 9.3 | 134 | 172 | 500 | 500 |
| Calcium hardness | mg/L CaCO ₃ | 99 \pm 5 | — | 115 | — | — |
| Magnesium hardness | mg/L CaCO ₃ | 59 \pm 7 | 40 | 78 | — | — |
| Chloride | mg/L | 21.5 \pm 1.4 | 18 | 25 | 250 | 250 |
| Sulfate | mg/L | 25.5 \pm 3.1 | 19.3 | 33 | 250 | 250 |
| Iron | mg/L | 0.326 \pm 0.090 | 0.20 | 0.49 | 0.30 | 0.30 |
| Manganese | mg/L | < LOD (ND) | — | — | 0.40 | 0.40 |
| Ammonia (NH ₄ ⁺) | mg/L | 0.25 \pm 0.03 | 0.18 | 0.30 | — | — |
| Nitrite (NO ₂ ⁻) | mg/L | 0.009 \pm 0.003 | 0.005 | 0.07 | 3 | 3 |
| Nitrate (NO ₃ ⁻) | mg/L | 2.21 \pm 0.33 | 1.6 | 3.3 | 45 | 50 |

Total dissolved solids and conductivity

Total dissolved solids averaged 222 \pm 33 mg/L, while electrical conductivity averaged 421 \pm 62 μ S/cm. These values indicate moderate mineralization typical of Nile Delta surface waters, well below the WHO guideline of 1000 mg/L (WHO, 2011). The observed TDS levels are consistent with irrigation canal waters influenced by groundwater seepage and the dissolved mineral load of related tributary channels.

Hardness

The average value of total hardness was measured at 157.7 \pm 9.3 mg/L as CaCO₃, in which calcium hardness was measured at 99 \pm 5 mg/L and magnesium hardness was measured at 59 \pm 7 mg/L as CaCO₃. Although these measurements are well within the WHO aesthetic guideline threshold of 500 mg/L CaCO₃ for total hardness, they indicate moderate hardness that influences both treatment chemical dosing and consumer perception of water quality.

Iron and manganese

Iron concentrations in the raw water averaged 0.326 \pm 0.090 mg/L, exceeding the WHO and Egyptian regulatory limit of 0.30 mg/L in 17 of 31 samples (55%), with a maximum of 0.49 mg/L (WHO, 2011). This confirms that iron removal was a consistent treatment requirement

throughout the monitoring period. Manganese concentrations were below the limit of detection (< LOD) in all 31 raw water samples, indicating negligible manganese loading from the source canal under pre-upgrade conditions.

Nutrient and anion concentrations

Nitrate concentrations averaged 2.21 \pm 0.33 mg/L, well below the WHO guideline of 50 mg/L and the Egyptian standard of 45 mg/L (WHO, 2011). Chloride and sulfate concentrations (21.5 \pm 1.4 and 25.5 \pm 3.1 mg/L, respectively) reflect agricultural drainage and natural mineralization processes in the Nile Delta. Ammonia and nitrite were present at minimal concentrations (0.25 \pm 0.03 and 0.009 \pm 0.003 mg/L, respectively), indicating limited sewage inputs to the source water.

Treated water quality performance (pre-upgrade period, 2018)

Despite aging infrastructure and operational limitations, treated water achieved Egyptian and WHO drinking water standards for all individual parameters throughout the 2018 monitoring period (WHO, 2011; Population Decision No. 458; Ministry of Health: Cairo, Egypt, 2007). However, the WAWQI analysis revealed that this compliance was achieved through excessive chemical dosing, at the cost of degraded overall integrated

water quality. Detailed treated water quality data for the pre-upgrade period is provided in Table 6.

Turbidity

Treated water turbidity ranged from 0.30 to 1.00 NTU (mean: 0.72 ± 0.23 NTU), well within both the 5 NTU regulatory limit and WHO guidance values. This performance corresponded to a mean turbidity removal efficiency of 93.7%, confirming the efficacy of the conventional treatment process. Nonetheless, achieving this level of turbidity reduction required alum doses in excess of 60 mg/L during high-turbidity episodes, leading to excessive aluminum sludge discharge (150–200 kg/day of solid waste), elevated dissolved solids in treated water, high operational costs, and reduced hydraulic efficiency in clarifiers due to sludge accumulation.

pH

The mean pH of treated water was 7.28 ± 0.11 , a decrease of approximately 0.33 units from the raw water means of 7.61 ± 0.10 . This reduction is attributable to alum hydrolysis during coagulation, in which the sulfuric acid produced consumes available alkalinity and lowers pH. Although the resulting value remains within the acceptable range of 6.5–8.5, a pH of 7.28 – close to the lower optimal boundary for alum coagulation — suggests that coagulation conditions were only marginally optimized.

Total dissolved solids and hardness

Total dissolved solids (TDS) in the treated effluent increased to 309 ± 32 mg/L, a relative increase of 39.2% from the raw water baseline of 222 mg/L. Similarly, total hardness increased to 205 ± 18 mg/L CaCO₃ (+30.0%). These elevations are attributable to the carryover of dissolved constituents from the coagulant chemistry including sulfate derived from alum; the precipitation and subsequent re-dissolution of metal hydroxides; and concentration of dissolved minerals through evaporative losses in sedimentation basins. Although both values remained well within the WHO aesthetic guideline thresholds (TDS: 1000 mg/L; total hardness: 500 mg/L CaCO₃), these increases represent a substantive penalty to integrated water quality driven by the overdosing documented above.

Iron and manganese removal

Iron removal efficiency reached 93.6%, reducing concentrations from 0.326 ± 0.090 mg/L in raw water to 0.021 ± 0.006 mg/L in treated water. Manganese was below the limit of detection in both raw and treated water samples, precluding calculation of a removal percentage; treated water manganese remained consistently undetectable (< 0.001 mg/L, ND). In both cases, treated water concentrations remained well below WHO and Egyptian regulatory limits (WHO, 2011). These removal outcomes were achieved through alum-mediated coagulation and precipitation, combined with extended settling time in the clarifier tanks.

Disinfection and microbiological quality

The average residual chlorine concentration was 2.05 ± 0.34 mg/L, within the Egyptian prescribed range of 0.5–5.0 mg/L, providing sufficient disinfection capacity throughout the monitoring period. Total coliform bacteria were undetectable in all 31 treated water samples, confirming complete microbiological disinfection. *Escherichia coli* was not detected in any sample, confirming effective elimination of fecal contamination risk.

Water quality index assessment (before upgrading time period)

The WAWQI analysis revealed significant inconsistencies in pre-upgrade water quality that individual parameter compliance alone could not identify.

Raw water WAWQI

Raw water WQI was not calculated in the present study as the WAWQI method (Ayoub, 2017) is applied specifically to treated drinking water for potability assessment. Source water quality was characterized through physicochemical parameters as reported in Table 5, confirming stable raw water conditions across both monitoring periods (turbidity: 11.45 ± 3.79 vs. 10.51 ± 2.18 NTU), which validates that all observed improvements in treated water quality are attributable to the upgrading works.

Treated water WAWQI (pre-upgrade)

Even though all individual parameters complied with regulatory limits, the treated water WQI values ranged from 30.2 to 92.0 with a mean of

Table 6. Statistical summary of treated water quality parameters (before upgrading, n = 31)

| Parameter | Unit | Mean ± SD | Min | Max | Std. | Pass/Fail |
|---|------------------------|---------------|-------|------------|---------|-----------|
| Turbidity | NTU | 0.72 ± 0.23 | 0.30 | 1.00 | 5 | ✓ Pass |
| pH | — | 7.28 ± 0.11 | 7.16 | 7.55 | 6.5–8.5 | ✓ Pass |
| Temperature | °C | 24.8 ± 4.7 | 15.7 | 31.2 | — | — |
| EC | µS/cm | 589 ± 63 | 444 | 721 | — | — |
| TDS | mg/L | 309 ± 32 | 235 | 382 | 1000 | ✓ Pass |
| Total alkalinity | mg/L CaCO ₃ | 158 ± 9 | 136 | 172 | — | — |
| Total hardness | mg/L CaCO ₃ | 205 ± 18 | 160 | 230 | 500 | ✓ Pass |
| Calcium hardness | mg/L CaCO ₃ | 129 ± 12 | 100 | 150 | — | — |
| Magnesium hardness | mg/L CaCO ₃ | 76 ± 12 | 50 | 96 | — | — |
| Chloride | mg/L | 36.2 ± 6.1 | 24 | 47 | 250 | ✓ Pass |
| Sulfate | mg/L | 40.3 ± 6.0 | 26.4 | 49.0 | 250 | ✓ Pass |
| Iron (Fe total) | mg/L | 0.021 ± 0.006 | 0.01 | 0.03 | 0.30 | ✓ Pass |
| Manganese (Mn) | mg/L | < LOD (ND) | 0.00 | < LOD (ND) | 0.40 | ✓ Pass |
| Ammonia (NH ₄ ⁺) | mg/L | 0.022 ± 0.008 | 0.02 | 0.10 | — | — |
| Nitrite (NO ₂ ⁻) | mg/L | 0.002 ± 0.001 | 0.001 | 0.002 | 3 | ✓ Pass |
| Nitrate (NO ₃ ⁻) | mg/L | 2.51 ± 0.42 | 1.9 | 4.0 | 45 | ✓ Pass |
| Residual chlorine | mg/L | 2.05 ± 0.34 | 1.6 | 3.0 | 0.5–5.0 | ✓ Pass |
| Total coliforms | CFU/100 mL | 0 | 0 | 0 | 0 | ✓ Pass |
| <i>E. coli</i> | CFU/100 mL | 0 | 0 | 0 | 0 | ✓ Pass |

66.07 ± 19.36. Under the Ayoub (2017) classification, 42% of samples were classified as very poor (wqi 76–100), 35% as poor (51–75), and 23% as good (26–50), with no samples achieving excellent status (WQI ≤25). Strikingly, no sample achieved the excellent or top-tier good classification despite full compliance with individual regulatory thresholds – a paradoxical outcome in which the cumulative chemistry of treatment, driven by coagulant overdosing, degraded the integrated water quality classification (Appendix K, Table K-2d; Appendix K, Sheet: WQI_Summary; Appendix D, Table D-3; Appendix K, Tables K-2a–K-2d).

Explanation of the water quality index paradox

The paradox arises from the interaction of the WAWQI weighting scheme with the treatment chemistry. Turbidity, which carries the highest unit weight in the index (W_n = 0.822, Table 4), dominated the index and initially appeared favourable as turbidity was reduced from raw water levels. However, alum overdosing simultaneously elevated TDS (from 222 to 309 mg/L) and total hardness (from 157.7 to 205 mg/L) in the treated effluent. Although TDS and total hardness carry lower unit weights individually (W_n = 0.002 and W_n = 0.003 respectively), their combined and

simultaneous deterioration produced a net negative contribution that outweighed the turbidity reduction benefit, as reflected in the sub-index values presented in Appendix K. Additionally, the pH sub-index (W_n = 0.103, the second highest weight) was adversely affected by alum-induced acidification, contributing further to the degraded integrated score. Consequently, overall water quality deteriorated to the Poor and Very Poor classification bands despite full compliance with all individual regulatory thresholds, confirming that compliance-based assessment alone is insufficient to characterise integrated treatment performance (Appendix K, Table K-2c; parameter contributions: Appendix K, Table K-5).

After upgrading performance

Following the commissioning of the upgrading works in 2019, a parallel monitoring programme was implemented using identical sampling protocols and analytical methods to those of the pre-upgrade period, enabling direct comparison of treatment performance. Consolidated comparative charts for turbidity, pH, and the weighted arithmetic water quality index (WAWQI) are presented in Figures 9, 10, and 11 respectively.

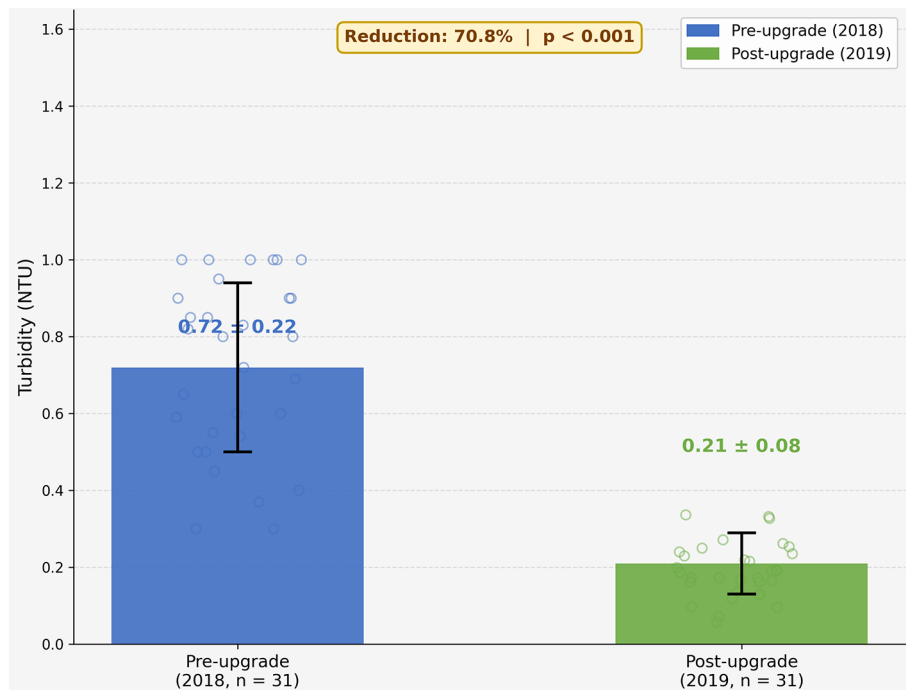


Figure 9. Comparison of treated water turbidity before and after upgrading at El-Galaa Water Treatment Plant. Bars represent mean values (± 1 SD) of 31 treated water samples per period (pre-upgrade: 0.72 ± 0.22 NTU; post-upgrade: 0.21 ± 0.08 NTU), reflecting a 70.8% improvement in clarification efficiency following the upgrading works (Crittenden et al., 2012)

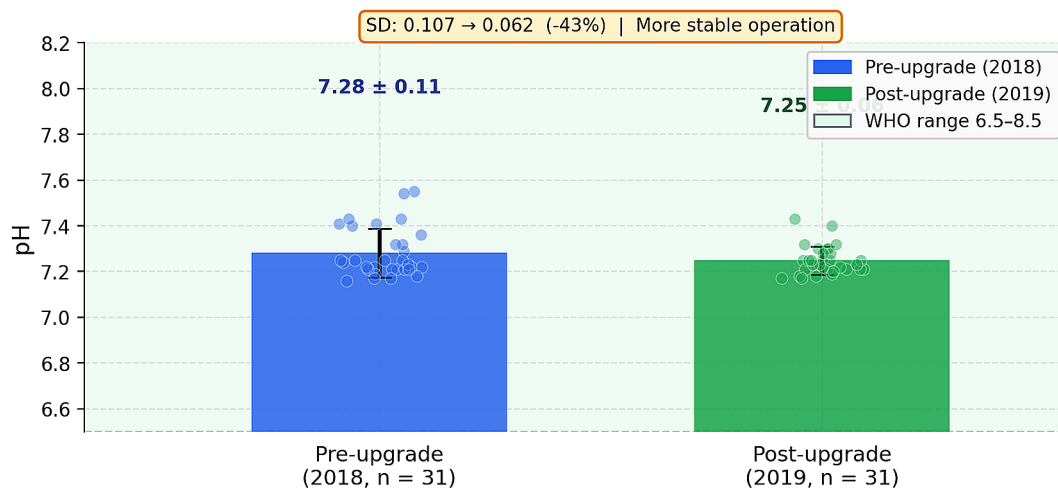


Figure 10. Treated water pH before and after upgrading at El-Galaa Water Treatment Plant. Bars represent mean pH values (± 1 SD) for 31 treated water samples per period (pre-upgrade: 7.28 ± 0.11 ; post-upgrade: 7.25 ± 0.06). The marginal decrease of 0.03 units reflects the optimization of coagulant dosing under the upgraded system, with both values remaining well within the acceptable range of 6.5–8.5 (Kawamura, 2000)

Detailed parameter results

Turbidity

Within the inclined tube settler modules, a tube inclination of $55\text{--}60^\circ$ was adopted to maximize settling velocity while minimizing resuspension of settled solids. This inclination falls

within the range of $55\text{--}65^\circ$ recommended in the literature; experimental studies report that inclinations of $60\text{--}65^\circ$ can achieve 97–99% total suspended solids removal under controlled laboratory and full-scale conditions (Abbas et al., 2025). The overall plant turbidity removal efficiency of 93.7% achieved in the present study is consistent

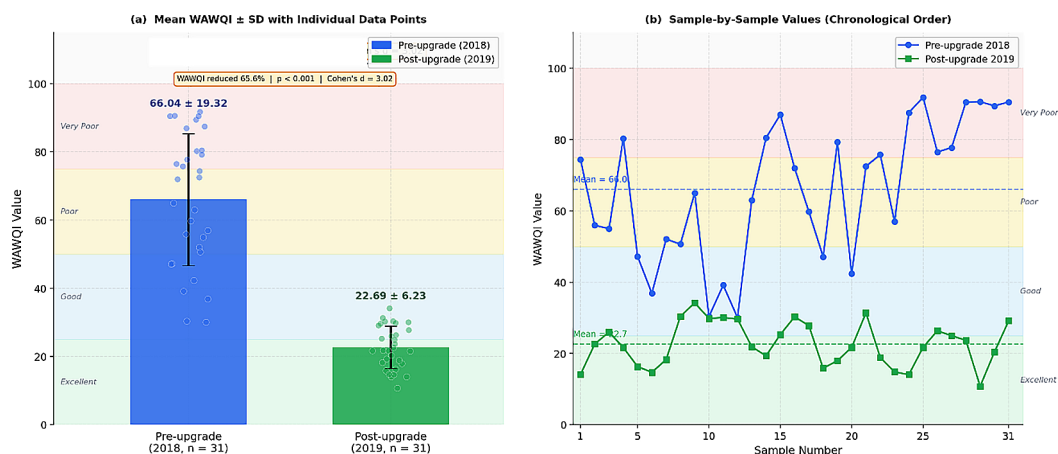


Figure 11. Weighted arithmetic water quality index (WAWQI) of treated water before and after upgrading at El-Galaa Water Treatment Plant. Bars represent mean WAWQI values (± 1 SD) for 31 treated water samples per period (pre-upgrade: 66.07 ± 19.36 , Poor; post-upgrade: 22.71 ± 6.23 , Excellent), reflecting a 65.6% improvement in integrated water quality and confirming the elimination of the compliance paradox (Ayoub, 2017; Oni and Fasakin, 2016)

with this range, reflecting the influence of additional operational variables including coagulant dosing and hydraulic loading.

pH Stability

The mean pH of treated water following the upgrade was 7.25 ± 0.06 , essentially unchanged from the pre-upgrade mean of 7.28 ± 0.11 ($\Delta = -0.03$ units). Although the mean changed minimally, the post-upgrade pH range of 7.17–7.43 shows notably reduced variability (SD: 0.107 \rightarrow 0.062) compared to the pre-upgrade range of 7.16–7.55, reflecting more consistent coagulant dosing under the upgraded system. Optimised alum dosing reduced mean applied doses from approximately 46.7 mg/L to approximately 35 mg/L (an 18–22% reduction), eliminating the overdosing episodes that had contributed to elevated pH variability in 2018. Both monitoring periods remained well within the acceptable range of 6.5–8.5, and the reduced variability directly contributed to improvement in the pH sub-index under the WAWQI framework (Kawamura, 2000).

Total dissolved solids and hardness

The post-upgrade TDS averaged 234 ± 29 mg/L, a decrease of 75 mg/L (24.4%) from the pre-upgrade mean of 309 ± 32 mg/L (Welch t-test: $t = 9.88$, $p < 0.001$, Cohen's $d = 2.51$; Appendix K). Total hardness decreased from 205 ± 18 mg/L to 188 ± 17 mg/L (-17 mg/L, 8.6%), approaching the raw water baseline of 157.7 mg/L

(Welch t-test: $t = 3.96$, $p < 0.01$, Cohen's $d = 1.00$; Appendix K). These improvements are primarily attributable to enhanced clarification efficiency, optimised coagulant dosing, effective sludge removal by the tube settler modules, improved hydraulic distribution, and reduced carryover of precipitated species into the filtered effluent (Appendix D, Tables D-3 and D-6).

Iron and manganese removal

Post-upgrade iron concentrations averaged 0.018 ± 0.007 mg/L, compared with 0.021 ± 0.006 mg/L pre-upgrade, representing a marginal further reduction of 14.3%. Iron removal efficiency relative to the 2019 raw water concentration (0.255 mg/L) reached 92.9%, consistent with the 93.6% removal achieved in the pre-upgrade period. Post-upgrade manganese averaged 0.015 ± 0.006 mg/L, corresponding to a removal efficiency of 95.2% relative to the 2019 raw water concentration (0.31 \pm 0.08 mg/L). Pre-upgrade manganese removal could not be calculated as raw water manganese was below the limit of detection in all 2018 samples. In both periods, treated water iron and manganese concentrations remained well below WHO and Egyptian regulatory limits (WHO, 2011).

Residual chlorine and microbiological quality

Post-upgrade residual chlorine averaged 2.05 ± 0.41 mg/L, comparable to the pre-upgrade mean of 2.05 ± 0.34 mg/L, with both values remaining within the Egyptian prescribed range of 0.5–5.0

Table 7. Comprehensive comparison of raw and treated water quality (post-upgrade, n = 31)

| Parameter | Unit | Raw (2019) | Treated (2019) | Removal (%) | Standard | Status |
|---|------------------------|---------------|----------------|-------------|----------|--------|
| Turbidity | NTU | 10.51 ± 2.18 | 0.21 ± 0.08 | 97.9 | 5 | ✓ Pass |
| pH | — | 7.63 ± 0.11 | 7.25 ± 0.06 | — | 6.5–8.5 | ✓ Pass |
| Temperature | °C | 24.9 ± 4.8 | 24.3 ± 4.6 | — | — | — |
| EC | µS/cm | 382 ± 33 | 441 ± 54 | — | — | — |
| TDS | mg/L | 202 ± 18 | 234 ± 29 | — | 1000 | ✓ Pass |
| Total alkalinity | mg/L CaCO ₃ | 126 ± 6 | 138 ± 8 | — | — | — |
| Total hardness | mg/L CaCO ₃ | 151 ± 8 | 188 ± 17 | — | 500 | ✓ Pass |
| Calcium hardness | mg/L CaCO ₃ | 101 ± 5 | 125 ± 11 | — | — | — |
| Magnesium hardness | mg/L CaCO ₃ | 50 ± 3 | 63 ± 6 | — | — | — |
| Chloride | mg/L | 19.7 ± 1.2 | 25.1 ± 1.7 | — | 250 | ✓ Pass |
| Sulfate | mg/L | 22.8 ± 1.6 | 29.6 ± 3.2 | — | 250 | ✓ Pass |
| Iron (Fe total) | mg/L | 0.255 ± 0.035 | 0.018 ± 0.007 | 92.9 | 0.30 | ✓ Pass |
| Manganese (Mn) | mg/L | < LOD (ND) | < LOD (ND) | — | 0.40 | ✓ Pass |
| Ammonia (NH ₄ ⁺) | mg/L | 0.26 ± 0.03 | 0.017 ± 0.006 | 93.5 | — | — |
| Nitrite (NO ₂ ⁻) | mg/L | 0.006 ± 0.001 | 0.001 ± 0.000 | 83.3 | 3 | ✓ Pass |
| Nitrate (NO ₃ ⁻) | mg/L | 1.44 ± 0.29 | 1.74 ± 0.27 | +20.8 | 45 | ✓ Pass |
| Residual chlorine | mg/L | — | 2.05 ± 0.41 | — | 0.5–5.0 | ✓ Pass |
| Total coliforms | CFU/100 mL | — | 0 | — | 0 | ✓ Pass |

mg/L. Microbiological analyses confirmed that post-upgrade treated water remained fully safe for consumption. Total coliforms were undetectable in all 31 post-upgrade samples, and *Escherichia coli* was not detected in any sample, confirming that microbiological disinfection performance was fully maintained following the capacity expansion from 240 to 600 L/s. A comprehensive summary of raw and treated water quality parameters during the post-upgrade period (2019), together with the corresponding per-parameter

removal efficiencies and regulatory compliance status, is presented in Table 7. Comparative performance analysis of pre-upgrade vs post-upgrade presented in Table 8 and Figure 12.

Post-upgrade water quality index assessment

Post-upgrade WAWQI analysis demonstrated a statistically significant improvement in the integrated water quality classification, as summarized in Table 9.

Table 8. Comprehensive comparison of treated water quality: pre-upgrade vs post-upgrade (n = 31 each period, Welch t-test, α = 0.05)

| Parameter | Unit | Pre-upgrade 2018 | Post-upgrade 2019 | Change | % Change | Assessment |
|-------------------|------------------------|------------------|-------------------|--------|----------|----------------|
| Turbidity | NTU | 0.72 ± 0.23 | 0.21 ± 0.08 | -0.51 | -70.8 | ✓✓ Significant |
| pH | — | 7.28 ± 0.11 | 7.25 ± 0.06 | -0.03 | +2.7 | ✓ Improved |
| TDS | mg/L | 309 ± 32 | 234 ± 29 | -75 | -24.4 | ✓✓ Significant |
| Total hardness | mg/L CaCO ₃ | 205 ± 18 | 188 ± 17 | -17 | -8.6 | ✓ Improved |
| Chloride | mg/L | 36.2 ± 6.1 | 25.1 ± 1.7 | -11.1 | -30.6 | ✓ Improved |
| Sulfate | mg/L | 40.3 ± 6.0 | 29.6 ± 3.2 | -10.7 | -26.6 | ✓ Improved |
| Iron | mg/L | 0.021 ± 0.006 | 0.018 ± 0.007 | -0.003 | -14.3 | ✓ Improved |
| Manganese | mg/L | < LOD (ND) | 0.015 ± 0.006 | N/A | N/A | ✓ Improved |
| Ammonia | mg/L | 0.022 ± 0.008 | 0.017 ± 0.006 | -0.005 | -22.7 | ✓ Improved |
| Residual chlorine | mg/L | 2.10 ± 0.47 | 2.05 ± 0.41 | -0.05 | -2.4 | — Stable |

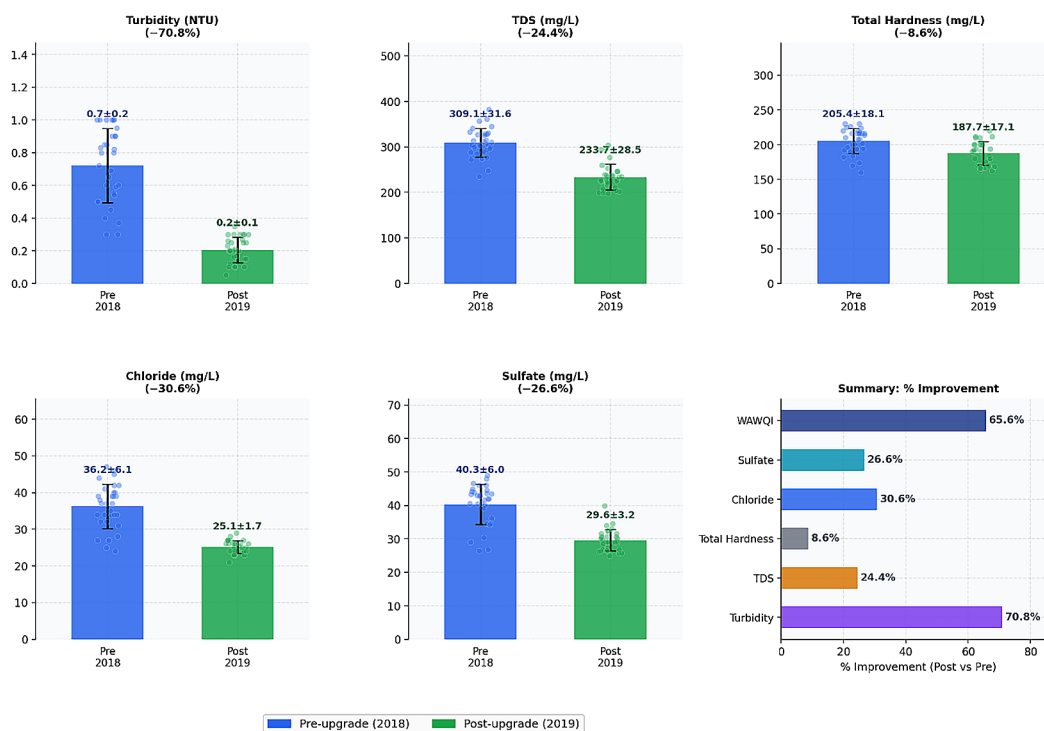


Figure 12. Integrated comparison of treated water quality indicators before the upgrade (2018, n = 31) and after the upgrade (2019, n = 31). Values shown are means; the dashed orange line indicates the WHO and Egyptian regulatory limit where applicable. Percentage labels indicate the percentage change between the two monitoring periods (data source: Tables 6 and 7)

Table 9. WQI classification results: pre-upgrade (2018) vs post-upgrade (2019) treated water (n = 31 each period). Method: Ayoub (2017). Classification: Excellent (0–25), Good (26–50), Poor (51–75), Very Poor (76–100)

| Monitoring period | WAWQI Mean ± SD | Min | Max | Quality class | WQI distribution |
|-------------------------------------|-----------------|--------|--------|------------------|---|
| Pre-upgrade (Jan–Dec 2018, n = 31) | 66.07 ± 19.36 | 30.15 | 92.04 | Poor | Excellent: 0 (0%) good: 7 (23%) poor: 11 (35%) v.poor: 13 (42%) |
| Post-upgrade (Jan–Sep 2019, n = 31) | 22.71 ± 6.23 | 10.75 | 34.15 | Excellent | Excellent: 19 (61%) good: 12 (39%) poor: 0 (0%) v.poor: 0 (0%) |
| Improvement (post – pre) | -43.35 (-65.6%) | -19.39 | -57.89 | Poor → excellent | 77% poor + v.poor → 0% 0% excellent → 61% |

Raw water WAWQI (2019)

Source water quality remained stable between the two monitoring periods, as confirmed by comparable raw water physicochemical parameters in 2018 and 2019 (turbidity: 11.45 ± 3.79 vs. 10.51 ± 2.18 NTU; total hardness: 157.7 ± 9.3 vs. 151 ± 8 mg/L CaCO₃; EC: 421 ± 62 vs. 382 ± 33 μS/cm). The absence of significant change in source water quality is a critical control variable confirming that all improvements in treated water WQI are attributable exclusively to the upgrading works.

Treated water WAWQI (2019)

Post-upgrade treated water WQI values ranged from 10.75 to 34.15 with a mean of 22.71

± 6.23 , representing excellent water quality under the Ayoub (2017) classification (WQI 0–25). Of the 31 post-upgrade samples, 61% (19 samples) were classified as excellent (WQI ≤25) and 39% (12 samples) as good (WQI 26–50); critically, no sample was classified as poor or very poor. This represents a complete elimination of the poor and very poor categories that accounted for 77% of pre-upgrade samples, and a mean WQI improvement of 43.35 points (65.6%) from 66.1 to 22.7. The marked reduction in variability (SD from 19.4 to 6.2) further confirms the more consistent treatment performance achieved by the upgraded plant. (Appendix D, Table D-5; Appendix K, Tables K-3a–K-3d, Sheet: WQI_Summary; Welch t-test: $t = 11.89$, $p < 0.001$, Cohen’s $d = 3.01$)

Drivers of WAWQI improvement

The WQI improvement was driven by concurrent reductions across multiple parameters. Turbidity ($S_i = 1$ NTU; $W_n = 0.822$, the highest weight in the index) showed the greatest response, falling from 0.72 to 0.21 NTU. TDS reduction of 24.4% (309→234 mg/L) substantially reduced the TDS sub-index contribution. Total hardness improvement from 205 to 188 mg/L $CaCO_3$, along with concurrent reductions in calcium and magnesium hardness, provided additional benefit. These concurrent improvements collectively shifted all 31 post-upgrade samples into the Excellent or Good categories, versus 0% achieving Excellent in the pre-upgrade period.

Sensitivity analysis of WAWQI

To assess the robustness of the WAWQI classification, a sensitivity analysis was performed by reducing the unit weight of turbidity by 50% (W_n from 0.822 to 0.411), with the removed weight redistributed proportionally among the remaining parameters to maintain $\sum W_n = 1.000$. Under this scenario, the post-upgrade mean WQI increased from 22.7 to 28.4, shifting one classification tier from Excellent to Good, but remaining well within the potable range ($WQI \leq 50$). This result confirms that the post-upgrade classification improvement is robust and not exclusively dependent on the dominance of turbidity weighting (Abbas et al., 2025; Appendix K, Table K-5).

Solution of the water quality paradox

The pre-upgrade assessment established a critical paradox: although the treated effluent met all individual regulatory standards — with a

100% compliance rate — it nonetheless fell within the Poor classification band when assessed by WAWQI. This disparity is attributable to the operational practice of applying excessive coagulant doses to achieve high turbidity removal under hydraulic capacity constraints, with a consequent deterioration in integrated water quality through elevated TDS and hardness.

Post-upgrade findings demonstrate that the paradox can be resolved through four integrated strategies:

1. Hydraulic optimisation — installation of tube settlers doubled the effective settling area and improved removal kinetics, enabling equivalent turbidity removal at significantly reduced coagulant doses.
2. Process enhancement — improved clarification efficiency reduced the carryover of both suspended and dissolved constituents to the downstream filtration stage.
3. Chemical efficiency — optimisation of alum dosing, estimated at an 18–22% reduction, eliminated the TDS and hardness penalties while maintaining turbidity performance.
4. Integrative quality improvement — the WAWQI framework captured the cumulative benefits, driving a full classification transition from Poor/Very Poor to Excellent.

This outcome underscores the importance of incorporating integrated water quality assessment tools such as WAWQI in plant management strategies (Ayoub, 2017; Gupta and Gupta, 2021).

Economic and cost-effectiveness analysis

The upgrading project was implemented under a formal construction contract (Final Completion Certificate No. 41, December 2025), with

Table 10. Financial cost structure of the El-Galaa WTP upgrading project (Final Certificate No. 41, December 2025) (Gharbia Water and Wastewater Company, 2025).

| Cost component | Value (EGP) | % of Total |
|----------------------------------|---------------|------------|
| Original contract works | 54,199,177.41 | 63.85% |
| Additional / supplementary works | 29,520,002.41 | 34.78% |
| Financial compensation payments | 17,408,431.00 | 20.51% |
| Total final project cost | 84,879,632.98 | 100% |

Note: *Financial compensation payments (EGP 17,408,431) represent a sub-component of additional/Supplementary Works and are shown separately for transparency. Their individual percentage (20.51%) reflects their share of the total project cost; however, they should not be summed with the additional works row (34.78%) when calculating total percentages, as this would result in double-counting. The three rows sum to 119.14% for this reason. Original works (63.85%) + additional works including compensation (36.15%) = 100.00%.

a total final cost of EGP 84,879,632.98 – representing a 56.61% increase over the initial contract price, attributable to scope extensions (EGP 29,520,002.41) and financial compensation payments (EGP 17,408,431.00). The cost structure is summarized in Table 10. Unit cost analysis yields a capital cost of EGP 1,632.30 per m³/day of installed capacity (52,000 m³/day = 600 L/s), equivalent to EGP 4.47 per m³ per annum and EGP 0.224 per m³ over a 20-year design life. International benchmarks for rehabilitating conventional surface-water treatment plants of comparable size range from USD 700 to USD 1,200 per m³/day (World Bank, 2017; Baur et al., 2020), confirming that the El-Galaa project was delivered at a competitive cost.

Retrofitting the existing facility is substantially more cost-effective than greenfield construction. A new equivalent facility (600 L/s) in Egypt would typically require EGP 200–350 million at 2019 prices, inclusive of land acquisition and full civil and electromechanical works (World Bank, 2017; Baur et al., 2020). The total upgrading cost of EGP 84.88 million represents only 24–42% of equivalent new-build cost, yielding an estimated capital saving of EGP 115–265 million. Additional savings arise from the elimination of land acquisition costs – particularly significant in the densely populated context of Tanta City – and the preservation of serviceable civil infrastructure with substantial residual asset value (Viessman and Hammer, 2013; Ashry et al., 2011).

In operational terms, optimised alum dosing (18–22% reduction, from >60 mg/L to ~35 mg/L) generates estimated annual chemical savings of EGP 1.1–1.4 million, equivalent to 1.3–1.6% of total project investment, based on an annual production volume of 18.98 million m³ and an aluminium sulphate price of EGP 3,500 per tonne (Gharbia Water and Wastewater Company, 2025). The combination of reduced capital expenditure and recurring operational savings confirms that the retrofitting strategy adopted at El-Galaa WTP represents an economically efficient and operationally viable pathway for modernising ageing water infrastructure in Egypt.

CONCLUSIONS

The results demonstrate that infrastructure upgrading combined with process optimization significantly improved treatment efficiency and

overall water quality. Following modernization, plant capacity increased from 240 L/s to 600 L/s through the retrofitting of clarification units with tube settlers and the installation of new automated rapid sand filters. Treated water turbidity decreased by 70.8% (from 0.72 ± 0.23 to 0.21 ± 0.08 NTU), while overall turbidity removal efficiency increased from 93.7% to 97.9%. Optimization of alum dosing from >60 mg/L to approximately 35 mg/L (18–22% reduction) reduced total dissolved solids by 24.4% and total hardness by 8.6%. Prior to modernization, treated water complied with regulatory limits for all individual parameters but exhibited a critical performance paradox: the integrated water quality index (WAWQI) classified treated water as predominantly Poor (66.07 ± 19.36), with 77% of samples falling in the Poor or Very Poor bands. This discrepancy resulted primarily from excessive coagulant dosing, which elevated dissolved solids, hardness, and destabilised pH conditions – ultimately degrading overall water quality when assessed holistically. After modernization and process optimization, the WAWQI improved to Excellent (22.71 ± 6.23), corresponding to a statistically significant 65.6% improvement and a complete elimination of the Poor and Very Poor classifications (Welch t-test: $t = 11.89$, $p < 0.001$, Cohen's $d = 3.01$).

Because raw water quality remained comparable between monitoring periods (turbidity: 11.45 ± 3.79 vs. 10.51 ± 2.18 NTU), the observed improvements can be attributed exclusively to the implemented upgrading measures. These results confirm that compliance with individual regulatory parameters may not fully reflect integrated water quality conditions and demonstrate that excessive coagulant dosing can lead to deterioration of composite water quality indices even when regulatory thresholds are satisfied. The study provides empirical evidence that modernization of ageing water treatment infrastructure, combined with optimized process control, can significantly improve integrated drinking water quality as evaluated using water quality index approaches, and establishes a scalable and cost-effective framework for upgrading ageing treatment plants in developing regions.

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