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Evaluating Water Use Efficiency and Water Treatment Systems at 1×1000 MW Coal-Fired Power Plants to Achieve Zero Liquid Discharge at PT XYZ

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ABSTRACT

Water-use efficiency is a strategic issue in large-scale coal-fired steam power plants, given the high operational water demand and the increasing need to implement the Zero Liquid Discharge (ZLD) concept. However, most previous studies have examined the performance of desalination systems, cooling processes, or wastewater treatment installations separately, thus failing to provide a comprehensive picture of water loss and Zero Liquid Discharge (ZLD) readiness at the system level. This study adopts an integrated operational water balance approach to analyse water-use efficiency, trace the main pathways of water loss, and evaluate the extent of Zero Liquid Discharge (ZLD) achieved at a 1×1000 MW coal-fired power plant (PT XYZ). A quantitative case study was conducted using four years of operational data (2019–2022) on seawater inflow, Reverse Osmosis (RO) performance, internal water-use patterns, and Wastewater Treatment Plant (WWTP) efficiency. The analysis results show that total water loss exceeded 60% of the annual volume of seawater taken, while the Reverse Osmosis (RO) recovery rate was low, at 6.07–6.19% during 2019–2021, before increasing to 11.85% in 2022. This condition indicates a significant gap between the system's actual performance and the Zero Liquid Discharge (ZLD) target. On the other hand, although the Wastewater Treatment Plant (WWTP) has consistently achieved pollutant removal efficiencies above 95%, its contribution to overall water recovery improvement remains relatively limited. These findings confirm that integrated water balance analysis can serve as an effective diagnostic tool for linking operational inefficiencies to Zero Liquid Discharge (ZLD) readiness levels and for providing lessons applicable to water management in power generation systems with high water-use intensity.

1. INTRODUCTION

Water-use efficiency has emerged as a critical issue in industrial sustainability, particularly in water-intensive sectors such as thermal power generation. (Liu et al, 2025). Increasing pressure on water resources, combined with stricter environmental regulations, has shifted industrial water management from a purely operational concern toward an integral component of pollution prevention strategies. (Kaya et al, 2025) (Zahedi et al, 2024). In coal-fired power plants, large volumes of water are required for cooling, steam generation, and wastewater treatment, making inefficiencies in water use a significant contributor to environmental impact and operational cost (Khan et al, 2024). In practice, thermal power plants experience substantial water losses through evaporation, blowdown, membrane rejection, and internal distribution inefficiencies (Junga et al, 2024a) (Seidabadi et al, 2024a). These losses not only reduce overall water-use efficiency but also constrain efforts to achieve Zero Liquid Discharge (ZLD), which is increasingly promoted as an advanced approach to industrial pollution control (Liao et al, 2025) (Plata et al, 2022). Although various technologies such as reverse osmosis (RO), wastewater treatment plants (WWTP), and cooling system optimization have been widely implemented, their performance is often evaluated separately, limiting a system-level understanding of water losses and recovery potential (Biedunkova et al, 2024) (Castelluccio et al, 2025).

In the Indonesian context, large-capacity coal-fired facilities such as PT XYZ (1×1000 MW) continue to encounter structural challenges in optimizing water utilization. Plant operational records reveal a pronounced disparity between total seawater intake and the volume effectively converted into productive use, indicating persistent water losses across desalination units, internal conveyance

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systems, and wastewater treatment operations. Despite the integration of advanced treatment technologies, including Sea Water Reverse Osmosis (SWRO), Brackish Water Reverse Osmosis (BWRO), and centralized Wastewater Treatment Plant (WWTP) infrastructure, the collective contribution of these systems to improving water-use efficiency and advancing Zero Liquid Discharge (ZLD) implementation remains insufficiently examined, particularly through analyses grounded in integrated operational datasets(Kresnaya et al, 2025) (NUGROHO et al, 2023). This gap underscores the need for approaches grounded in systems thinking and mass-balance theory to quantify resource flows across interconnected subsystems.

Previous investigations into water management in power plants predominantly adopt reductionist perspectives, focusing on discrete performance indicators such as desalination recovery rates, cooling efficiency, or wastewater quality compliance(Bueso et al, 2024a) (Hasnira et al, 2025). While such studies provide valuable technical insights, they inadequately capture the system-wide behaviour of water flows, including accumulation, dissipation, and recovery pathways. The absence of integrated operational models constrains the ability to (i) quantify total water losses at the plant level, (ii) interpret Reverse Osmosis (RO) performance within broader utilization dynamics, and (iii) evaluate the operational gap relative to Zero Liquid Discharge (ZLD) targets using measurable system indicators. From a theoretical standpoint, this fragmentation reflects a lack of alignment with process integration theory and resource flow analysis frameworks (Davydenko et al, 2023).

To address these limitations, this study adopts an integrated operational water-balance framework anchored in mass-conservation principles and systems analysis. The research pursues four objectives: first, to quantify plant-level water losses and recovery rates through a comprehensive water-balance model) (second, to evaluate Reverse Osmosis (RO) performance as a determinant of resource efficiency) (third, to assess the functional contribution of the Wastewater Treatment Plant (WWTP) within water reuse and pollution prevention strategies) (and fourth, to measure the discrepancy between current operational conditions and Zero Liquid Discharge (ZLD) requirements using quantifiable indicators.

The principal contribution of this research resides in the deployment of a comprehensive operational water-balance framework to systematically identify inefficiency pathways and assess readiness for Zero Liquid Discharge (ZLD) implementation using multi-year, plant-level data. By interconnecting desalination efficiency, internal water allocation patterns, and wastewater treatment outcomes within a unified analytical framework, this study advances a transferable methodological approach to enhance water-use efficiency and strengthen pollution-prevention strategies in thermal power plants and other water-intensive industrial systems.

2. METHODS

This study employed a quantitative-descriptive case study design to evaluate the efficiency of the water management system at PT XYZ's 1,000 MW coal-fired power plant. This approach enabled the numerical measurement of the observed operational variables, providing an accurate representation of the system's condition during the 2019–2022 research period. All water management subsystems, Sea Water Reverse Osmosis (SWRO), Brackish Water Reverse Osmosis (BWRO), Wastewater Treatment Plant (WWTP), and Sewage Treatment Plant (STP), were analysed as an integrated system in the power plant's water balance.

The research data consisted of primary data, including monthly operational reports, inflow–outflow data, permeate production, demineralized water, and losses, as well as effluent quality test results from the Wastewater Treatment Plant (WWTP) and Sewage Treatment Plant (STP). Secondary data used Sea Water Reverse Osmosis or Brackish Water Reverse Osmosis (SWRO/BWRO) design specification documents and quality standards applicable in government regulations 22 of 2021 and technical approval S.134/2021. The research variables included the efficiency of Sea Water Reverse Osmosis (SWRO) and Brackish Water Reverse Osmosis (BWRO) based on recovery values, water balance components (inflow, utilization, and losses), permeate quality, Wastewater Treatment Plant or Sewage Treatment Plant (WWTP/STP) removal efficiency, and the level of effluent compliance with quality standards.

Data analysis was conducted through: (1) calculation of reverse osmosis efficiency using the ratio of permeate to feed water) ((2) water balance analysis to determine the distribution and amount of water loss. These two parameters are used to assess the overall effectiveness of water management and to determine the unit's position relative to efficiency improvement targets and the direction of Zero Liquid Discharge (ZLD) implementation. The formula can be seen below.

1. Reverse Osmosis Efficiency Calculation (Recovery)

The efficiency of a Reverse Osmosis (RO) unit is assessed by its recovery, which is the proportion of feed water that is successfully converted into permeate. Recovery is used to quantitatively evaluate the performance of Sea Water Reverse Osmosis (SWRO) and Brackish Water Reverse Osmosis (BWRO). Mathematically, the recovery value is given by formula (1).

$$Recovery\ (\%) = \frac{Q\ Permeate}{Q\ feed}\ x\ 100\% \qquad (1)$$

Q permeate is the permeate water discharge produced (m^3/h or m^3/month), Q Feed is the total feed water discharge entering the Reverse Osmosis (RO) unit (m^3/h or m^3/month).

2. Water Balance Formulation

The water balance is formulated to describe the quantitative relationship between total water inflow, water utilization, and water losses. The basic water balance formulation is expressed as (2) and (3):

$$Q\ inflow = Q\ utilization + \ Qlosses \qquad (2)$$

$$Q\ losses = Qinflow - Qutilization \qquad (3)$$

In preparing the water balance, Q_{inflow} Is defined as the total volume of water entering the system, including seawater supply and make-up water. Meanwhile, $Q_{\text{utilization}}$ Is the total water used for operational needs, including permeate production, demineralized water, potable water, and service water. Meanwhile, Q_{losses} Reflects the amount of water lost during the process, which comes from RO reject, blowdown, filtration unit backwash, evaporation in the cooling tower, sludge disposal, and potential leaks in the distribution network. The formulas are (4) and (5).

$$Losses\ (\%) = \frac{Q_{\text{losses}}}{Q_{\text{inflow}}} \times 100\% \qquad (4)$$

$$\text{Water Recovery (\%)} = \frac{Qutilization}{Q_{\text{inflow}}} \times 100\% \qquad (5)$$

To assess the proportion of water loss relative to the total supply, the loss value is calculated as a percentage by comparing Q_{losses} and Q_{inflow}. Meanwhile, the rate of clean water utilization is evaluated as the percentage of water recovered, calculated as the ratio of cap Q sub utilization to Q_{inflow}. Then, the following steps involved descriptive statistics to analyse effluent quality parameters and compliance with quality standards, and a gap analysis to identify differences between actual performance and design capacity for each subsystem.

3. Reverse Osmosis (RO) performance

An evaluation of the performance of the Reverse Osmosis (RO) system at Unit 1x1000 MW was conducted by analyzing the number of losses and the RO system's efficiency over the 2019–2022 period. In general, losses are the difference between the total seawater inflow and the amount of water successfully processed into Brackish Water Reverse Osmosis (BWRO) products, demineralized water, and potable and service water. Therefore, the number of losses can serve as an indirect indicator of the effectiveness of the pretreatment process, the level of membrane fouling, and the efficiency of water distribution in the system. Losses in the water treatment system are calculated to quantify the amount of water lost during production. The value of losses is obtained by subtracting the total amount of water successfully utilized as output, namely Brackish Water Reverse Osmosis (BWRO) product water, potable water, service water, and demineralized water, from the total inflow of seawater entering the system. Mathematically, the calculation of losses is formulated (6).

$$Losses = \ Seawater\ Inflow\ - \\ (BWRO\ Output\ + \ Potable\ Service\ + \ Denim) \qquad (6)$$

The formula shows that the greater the difference between inflow and total output, the higher the rate of water loss in the system, which is generally caused by Reverse Osmosis (RO) reject, blowdown, evaporation, or distribution inefficiency.

Reverse Osmosis (RO) efficiency assesses a Reverse Osmosis unit's ability to produce permeate water relative to the total raw water entering the system. This efficiency is calculated as the ratio of the volume of Brackish Water Reverse Osmosis (BWRO) output to the volume of seawater inflow, then converted to a percentage. The Reverse Osmosis (RO) efficiency formula is expressed as (7):

$$Efisiensi\ RO = \frac{Output\ BWRO}{Inflow\ Air\ Laut}\ x\ 100 \qquad (7)$$

High Reverse Osmosis (RO) efficiency indicates good membrane condition, optimal pretreatment, and stable operating conditions.

2.1. Research Design and Analytical Approach

This research employs a quantitative descriptive case study methodology to examine water-use efficiency in a large-scale coal-fired power plant. The analysis utilizes a complete set of operational data spanning 2019–2022, representing the full population of plant records rather than a statistical sample. Accordingly, the study emphasizes a system-level diagnostic assessment rather than inferential statistical testing. Such a methodological orientation is consistent with industrial water audits and operational performance evaluations, in which analytical rigor derives from mass-balance integrity and temporal consistency rather than hypothesis-driven statistical inference (Macknick et al, 2012) (Sophia L.(Macknick et al, 2012) (Plata et al, 2022).

The analytical structure combines water balance modelling, evaluation of Reverse Osmosis (RO) recovery performance, comparative analysis of subsystem outputs, and gap assessment relative to Zero Liquid Discharge (ZLD) criteria. This integrated framework facilitates systematic identification of dominant inefficiency mechanisms across desalination processes, internal water allocation networks, and wastewater treatment operations.

2.2. Data Quality Control and Verification

To ensure data reliability and analytical reproducibility, a structured verification protocol was applied. Monthly operational datasets were validated through cross-referencing with plant operational logs, internal monitoring systems, and subsystem production documentation. The data screening procedure consisted of: (i) Examination of inflow–outflow coherence using mass balance closure principles) ((ii) Detection of irregular values via inter-period consistency checks) ((iii) Removal of incomplete datasets where reconciliation was infeasible) ((iv) Application of linear interpolation exclusively for short-duration missing values (≤ one reporting interval).

Outlier identification relied on consistency validation among seawater intake volumes, Brackish Water Reverse Osmosis (BWRO) production output, demineralized water generation, and documented water losses. This approach conforms to established industrial monitoring and audit practices for system-oriented operational studies (Davydenko et al, 2023a).

2.3. Assumptions and Boundary Conditions

The water balance model was developed under defined operational assumptions and system boundaries. The analytical scope covers the plant's operational water cycle, including seawater intake, Sea Water Reverse Osmosis or Brackish Water Reverse Osmosis (SWRO/BWRO) desalination systems, the demineralization unit, internal distribution networks, wastewater treatment facilities, Wastewater Treatment Plant, and Sewage Treatment Plant (WWTP and STP). Seasonal variability was represented through monthly aggregation over a four-year dataset.

Minor unmetered losses and leakage effects were incorporated as residual terms within the balance structure. Flow measurement uncertainty was assumed within ±2–5%, consistent with standard industrial tolerances. Plant operations were near steady-state during most of the observation period, supporting a consistent mass-balance interpretation.

2.4. Uncertainty Consideration and Robustness

Although formal statistical uncertainty quantification or sensitivity analysis was not performed, the robustness of the findings is supported by several empirical considerations. These include the consistency of multi-year operational trends, the dominant magnitude of observed water losses exceeding 60% of total inflow, the relative stability of Reverse Osmosis (RO) recovery behavior, and the persistently high pollutant removal efficiencies achieved by the Wastewater Treatment Plant (WWTP), which consistently exceeded 95%.

Given that the scale of the detected inefficiencies substantially surpasses potential measurement deviations, the principal conclusions regarding dominant water-loss pathways and Zero Liquid Discharge (ZLD) readiness are considered methodologically robust. This approach is consistent with system-level industrial performance evaluations, in which the analytical emphasis is on magnitude dominance and trend consistency rather than on probabilistic uncertainty modeling.

3. RESULT AND DISCUSSION

Key Performance Indicators (KPIs)

To ensure consistent longitudinal assessment over the 2019–2022 observation period, a standardized set of Key Performance Indicators (KPIs) was established. These indicators reflect overall water-use efficiency, desalination performance, and wastewater treatment effectiveness at the system level. The following Key Performance Indicators (KPIs) were consistently applied across the 2019–2022 observation period:

(1) Total Water Loss Ratio (%)

This indicator measures the share of total seawater inflow that is not converted into productive water use within the system. It represents cumulative losses associated with evaporation, membrane rejection flows, blowdown discharge, and inefficiencies in internal distribution.

$$Total\ Water\ Loss\ Ratio\ (\%) = \frac{Total\ Water\ Loss}{Total\ Seawater\ Inflow}\ x\ 100 \qquad (8)$$

(2) Reverse Osmosis (RO) Recovery Rate (%)

This indicator evaluates the effectiveness of the Reverse Osmosis (RO) system in converting seawater inflow into usable permeate. It functions as a key measure of desalination performance.

$$RO\ Recovery\ Rate\ (\%) = \frac{BWRO\ Output}{Total\ Seawater\ Inflow}\ x\ 100 \qquad (9)$$

Elevated recovery values signify more efficient membrane utilization and lower reject volumes, both of which are critical for improving overall water-use efficiency and minimizing environmental discharge.

(3) Water Utilization Efficiency (%)

This indicator reflects the fraction of total seawater inflow that is successfully converted into productive water for downstream operations, including demineralization and internal distribution.

$$\text{Water Utilization Efficiency (\%)} = \frac{Total\ Product\ Water}{Total\ Seawater\ Inflow}\ x\ 100 \qquad (10)$$

These Key Performance Indicators (KPI) represent overall system effectiveness beyond isolated subsystem performance, offering an integrated metric of operational water productivity.

(4) Wastewater Treatment Plant (WWTP) Removal Efficiency (%)

This indicator assesses the wastewater treatment plant (WWTP) performance in removing pollutants from process effluents before discharge or reuse.

$$\text{WWTP Removal Efficiency (\%)} = \frac{Influent\ Concentration - Effluent\ Concentration}{Influent\ Concentration}\ x\ 100$$

While this metric primarily reflects water quality performance, Wastewater Treatment Plant (WWTP) efficiency also indirectly affects Zero Liquid Discharge (ZLD) readiness by influencing the potential for treated effluent reuse within the plant system.

Water Balance Performance during the Stability Phase (2019–2021)

Table 1. Water Balance of the 1x1000 MW unit in 2019

Month	Seawater Inflow (m^3)	BWRO Output (m^3)	Demin Production (m^3)
January	102.500	5.800	25.500
February	96.200	5.450	24.800
March	104.300	6.250	26.300
April	105.900	6.300	26.100
May	107.200	6.350	26.450
June	107.900	6.400	26.650
July	105.500	6.150	26.000
August	103.800	6.250	26.100
September	102.900	6.200	25.850
October	105.600	6.350	26.400
November	107.000	6.400	26.300
December	106.591	6.100	24.550
Total	**1.259.391**	**77.950**	**315.000**

Table 2.

Water Balance of the 1x1000 MW unit in 2020.

Month	Seawater Inflow (m^3)	BWRO Output (m^3)	Demin Production (m^3)
January	97.800	5.600	24.800
February	91.500	5.150	23.900
March	98.900	5.850	25.100
April	99.200	5.900	24.600
May	100.400	5.950	24.900
June	101.300	6.000	25.050
July	99.800	5.850	24.500
August	98.600	5.900	24.700
September	97.900	5.850	24.400
October	99.400	5.900	24.750
November	100.200	6.000	25.000
December	100.660	5.950	22.300
Total	**1.185.660**	**72.000**	**299.000**

Table 3.

Water Balance of the 1x1000 MW unit in 2021

Month	Seawater Inflow (m^3)	BWRO Output (m^3)	Demin Production (m^3)
January	98.500	5.450	24.300
February	92.300	5.200	23.900
March	100.200	6.100	25.050
April	101.800	6.150	24.900
May	103.600	6.200	25.100
June	104.200	6.300	25.350
July	102.900	6.000	24.950
August	100.500	6.100	25.200
September	99.000	6.050	24.800
October	102.700	6.200	25.350
November	104.275	6.250	25.350
December	103.500	6.022	24.702
Total	**1.213.475**	**73.972**	**302.652**

A system-level assessment of plant operations during 2019–2021 shows stable yet suboptimal performance, marked by limited desalination recovery and consistently elevated water loss ratios. Over these three years, annual seawater intake remained between 1.18 and 1.26 million m^3, indicating relatively steady operating conditions without major disruptions.

Although minor variations in inflow volumes were observed, Brackish Water Reverse Osmosis (BWRO) permeate production remained proportionally constrained, yielding Reverse Osmosis (RO) recovery rates of 6.19% (2019), 6.07% (2020), and 6.10% (2021). The minimal variation across years (±0.06%) indicates an operational plateau in desalination performance, suggesting no significant structural adjustments or technological enhancements during this period.

Demineralized water production remained stable at approximately 315,000 m^3 per year, indicating consistent downstream water requirements. However, when evaluated relative to total seawater intake, effective water utilization remained limited, not exceeding 25–27% of annual inflow. As a result, overall water loss ratios consistently exceeded 65%, indicating that a substantial portion of the intake water did not translate into productive system output.

The coexistence of low Reverse Osmosis (RO) recovery and high loss ratios indicates that inefficiencies were structurally embedded within the system rather than arising from short-term operational fluctuations. From a Zero Liquid Discharge (ZLD) standpoint, the 2019–2021 period can therefore be characterized as a phase of operational stability with limited progress in efficiency improvement. The lack of measurable progress underscores the need for targeted optimization efforts, particularly in desalination recovery performance and reject-stream management, to mitigate system-level water losses.

Operational Shift and Performance Improvement in 2022

Table 4.

Water Balance of the 1x1000 MW unit in 2022

Month	Seawater Inflow (m^3)	BWRO Output (m^3)	Demin Production (m^3)
January	125.500	13.800	22.500
February	118.200	13.100	21.700
March	128.800	15.300	23.200
April	130.100	15.400	23.500
May	131.900	15.550	23.700
June	133.200	15.600	23.800
July	131.500	15.400	23.050
August	130.200	15.500	23.250
September	129.500	15.450	22.900
October	132.300	15.500	23.100
November	134.700	15.600	23.150
December	134.978	16.134	22.386
Total	**1.580.938**	**187.334**	**271.236**

The 2022 operational results show a clear departure from the trend of stability observed between 2019 and 2021. Total seawater intake rose markedly to 1,580,938 m^3, representing an increase of approximately 26% relative to the average inflow recorded during the previous three years. More notably, BWRO permeate production reached 187,334 m^3, yielding an RO recovery rate of 11.85%.

Relative to the three-year average recovery rate of 6.12% (2019–2021), this outcome reflects a substantial improvement of roughly 94%. Such a pronounced increase suggests implementing operational optimization initiatives, potentially involving enhanced membrane performance, adjustments to operating parameters, or targeted maintenance interventions.

Despite the improvement in desalination recovery, overall system efficiency remained fundamentally constrained. The total water loss ratio in 2022 was approximately 63.3%, only slightly lower than the average value of about 65% observed during the earlier stability phase. This indicates that although RO performance improved, system-level inefficiencies persisted due to ongoing losses from rejection streams, evaporation, and blowdown.

From a Zero Liquid Discharge (ZLD) standpoint, the 2022 recovery rate remains significantly below the levels typically reported for high-recovery membrane systems in advanced Zero Liquid Discharge (ZLD) configurations (>70%). Accordingly, the performance shift observed in 2022 is better interpreted as operational optimization rather than a structural technological transition. Although the plant showed operational adaptability, achieving Zero Liquid Discharge (ZLD) readiness requires structural optimization.

The results, therefore, underscore a critical distinction between improvements in operational efficiency and broader system-level transformation of water circulation. Although operational optimization can generate measurable short-term gains, achieving circular water management objectives requires an integrated redesign strategy that addresses reject management, evaporation reduction, and high-recovery desalination technologies.

Dominant Water Loss Pathways

Mass-balance evaluation indicates that RO reject streams are the largest contributor to total water losses. Based on recovery–reject relationships, reject streams are estimated to account for roughly 45–55% of annual losses. Cooling tower evaporation accounts for approximately 20–30%, while blowdown and internal distribution losses make up the remainder.

Although these proportions are derived from aggregate mass-balance calculations rather than direct sub-metering, the overall pattern is consistent. The dominance of reject streams suggests that desalination recovery performance exerts a stronger influence on total system efficiency than other loss mechanisms. Therefore, incremental improvements in evaporation control alone would likely produce a limited impact compared with recovery-focused strategies.

3.5. Longitudinal KPI Comparison (2019–2022)

Table 5.

Longitudinal Performance Indicators (2019-2022)

Indicator	2019	2020	2021	2022	2019–2021 Avg.	Relative Change 2022 vs Avg.
Seawater Inflow (m^3)	1,259,391	1,185,660	1,213,475	1,580,938	1,219,509	26%
RO Recovery (%)	6.19	6.07	6.1	11.85	6.12	94%
Water Utilization Efficiency (%)	25.0	25.2	24.9	17.2	25.0	-31%
Water Loss Ratio (%)	65.6	65.5	65.6	63.3	65.6	−3.5 %

WWTP Removal Efficiency (%)	>90	>94	>99	>95	—	Stable

When assessed longitudinally, performance during 2019–2021 remained largely unchanged. During this period, the average Reverse Osmosis (RO) recovery rate was 6.12%, while the water loss ratio consistently remained above 65%, highlighting structural inefficiencies in the system.

In contrast, the 2022 operational data show a pronounced shift in performance. Reverse Osmosis (RO) recovery improved by approximately 94% relative to the three-year baseline, whereas the water loss ratio decreased by only 3.5%. This disparity suggests that although desalination efficiency increased substantially, system-level losses continued to dominate overall performance. Accordingly, the improvement observed in 2022 is more appropriately characterized as partial operational optimization rather than a structural progression toward Zero Liquid Discharge (ZLD).

Furthermore, overall Water Utilization Efficiency declined in 2022 because the expansion of total seawater intake outpaced the corresponding gains in productive water output, thereby diminishing the net impact of subsystem-level efficiency enhancements.

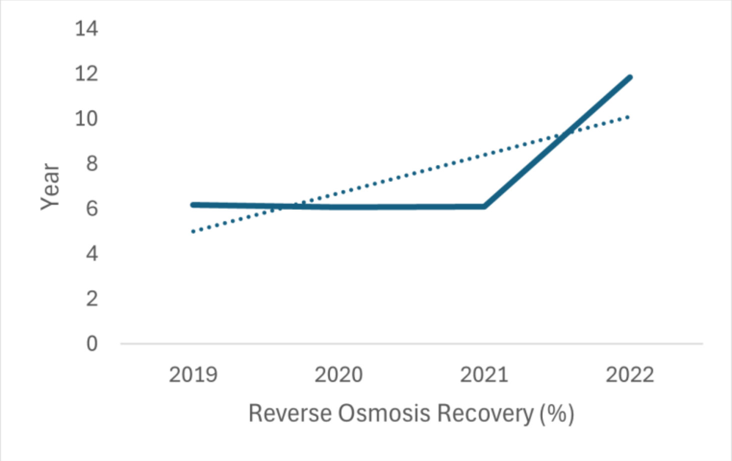

Figure 1. Trend of Reverse Osmosis Recovery (2019 – 2022)

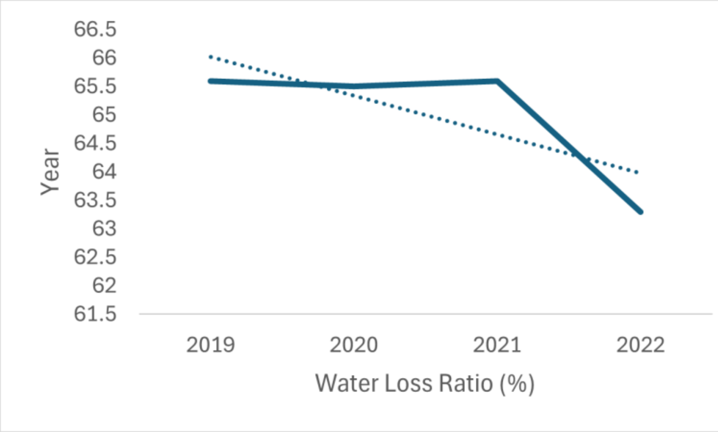

Figure 2. Trend of Water Loss Ratio (2019-2022)

Figure 1 presents the longitudinal trajectory of Reverse Osmosis (RO) recovery performance, highlighting a prolonged operational plateau from 2019–2021, followed by a pronounced increase in 2022. Figure 2 demonstrates that, notwithstanding the significant improvement in RO recovery, the overall water loss ratios remained persistently high. This pattern indicates that systemic inefficiencies continued to dominate plant-level water performance.

3.6. Wastewater Treatment Effluent Quality Compliance and Removal Efficiency (2019-2022)

Table 6. Summary of effluent compliance

Parameter	Standard	2019 Eff. (%)	2020 Eff. (%)	2021 Eff. (%)	2022 Eff. (%)
pH	6–9	Compliant	Compliant	Compliant	Compliant
BOD	30 mg/L	90	94	96.4	99.6
COD	100 mg/L	92	96	99.3	95.8
TSS	100 mg/L	88	92	99.1	92.6
Oil & Grease	5 mg/L	85	90	98.2	85.8
Ammonia	10 mg/L	96	97	99.97	99.8
Total Coliform	3000/100 mL	90	94	99.98	99.85

Table 6 presents a summary of effluent compliance and pollutant removal efficiencies of the Wastewater Treatment Plant (WWTP) over the 2019–2022 observation period. Removal efficiencies for Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) consistently remained above 90%, with maximum values exceeding 99% during 2021–2022. Similarly, Total Suspended Solids (TSS) and ammonia removal efficiencies were maintained at high levels (>92–99%), while effluent Potential of Hydrogen (pH) remained near neutral (7.5–7.9), indicating consistent treatment performance.

Although slight fluctuations in efficiency were recorded in 2022, all effluent parameters continued to meet applicable regulatory standards. Nevertheless, despite the high effectiveness of pollutant removal, the volumetric contribution of treated effluent to overall water recovery remains relatively minor compared with total seawater intake. Taken together, while the Wastewater Treatment Plant (WWTP) effectively supports environmental compliance objectives, its impact on mitigating structural-system-level water losses remains limited.

3.7. Drivers of System Inefficiency

The primary source of inefficiency in the plant's water management system is limited Reverse Osmosis (RO) recovery and the resulting reject streams. Membrane fouling and scaling reduce permeability and increase reject volumes, thereby limiting effective water utilization. Additionally, fluctuations in inlet water characteristics and departures from optimal operating parameters, particularly pressure and flow rate, further impede recovery performance. While routine maintenance procedures, including cleaning-in-place (CIP), may temporarily enhance membrane efficiency, the sustained presence of elevated reject fractions suggests that incremental maintenance strategies alone are insufficient to meaningfully mitigate system-level losses. These results indicate that the observed inefficiencies are structurally inherent to the desalination system configuration rather than arising exclusively from short-term operational variability.

3.8. Gap Analysis Toward Zero Liquid Discharge (ZLD)

Despite the performance improvement observed in 2022, Reverse Osmosis (RO) recovery increased to only 11.85%, which remains significantly lower than the recovery levels commonly associated with high-efficiency membrane systems (>70%) in Zero Liquid Discharge (ZLD) oriented configurations. Furthermore, total water loss ratios exceeding 63% indicate that the system continues to operate well below circular water reuse conditions. These results imply that achieving Zero Liquid Discharge (ZLD) in a 1×1000 MW coal-fired power plant requires a structural technological transformation rather than incremental operational optimization.

3.9. Economic and Operational Constraints of ZLD Implementation

While Zero Liquid Discharge (ZLD) can be achieved through the integration of high-recovery membrane systems, brine concentration technologies, and crystallization units, its application in large-scale ultra-supercritical power plants is constrained by significant technical and economic challenges. First, Zero Liquid Discharge (ZLD) implementation requires substantial capital investment, particularly for brine concentrators and thermal crystallization infrastructure. Second, higher recovery targets require higher operating pressures, which in turn increase energy demand and operating expenses. Third, high-salinity feed streams increase the risk of membrane fouling and scaling, potentially compromising system reliability. Additionally, scalability limitations become significant due to the large volumetric flow rates inherent to 1×1000 MW plant operations. Accordingly, although Zero Liquid Discharge (ZLD) is a desirable environmental target, a staged approach emphasizing progressive efficiency improvements may be more economically feasible than immediate full-scale Zero Liquid Discharge (ZLD) adoption.

3.10 System-Level Implications

The overall findings highlight an important distinction between environmental compliance and circular water efficiency. Although the Wastewater Treatment Plant (WWTP) consistently achieves high pollutant removal, the dominant source of inefficiency remains limited desalination recovery and elevated reject volumes. Accordingly, optimization efforts targeting membrane recovery and reject stream management offer the greatest potential to reduce total water losses.

From a broader water–energy nexus perspective, this case study demonstrates that achieving quantitative water circularity in large-scale thermal power plants requires integrated technological restructuring rather than isolated improvements at the subsystem level. These findings contribute to the ongoing discourse on the feasibility of implementing Zero Liquid Discharge (ZLD) in large-scale energy systems.

CONCLUSION

This study evaluated water-use efficiency and Zero Liquid Discharge (ZLD) readiness in a 1×1000 MW coal-fired power plant using a longitudinal Key Performance Indicator (KPI)-based approach. The analysis shows that although plant operations appeared stable during 2019–2021, water-use performance remained structurally inefficient. Reverse Osmosis (RO) recovery was consistently low (≈6.12%), while total water loss ratios exceeded 65%, indicating that a substantial portion of intake water was not effectively converted into productive use.

A clear operational shift occurred in 2022. Reverse Osmosis (RO) recovery increased significantly (+94% relative to the 2019–2021 average). However, the overall water loss ratio decreased only marginally (−3.5%). This imbalance suggests that improvements at the subsystem level do not automatically translate into proportional gains in system-level water efficiency. Mass balance evaluation further shows that RO reject streams account for the largest share of total losses (approximately 45–55%), followed by evaporation and blowdown. In practical terms, recovery performance remains the most critical leverage point for improving overall efficiency.

While the Wastewater Treatment Plant (WWTP) consistently achieved high pollutant removal efficiencies, compliance with discharge standards alone does not equate to circular water performance. The findings highlight an important distinction between environmental compliance and quantitative water-reuse efficiency in large-scale thermal power systems.

To make meaningful progress toward ZLD, incremental adjustments are unlikely to be sufficient. A phased strategy with measurable targets—such as increasing RO recovery to 20–25% and reducing total water losses below 55% within five years—would represent a more realistic transition pathway. Achieving this would require improvements in membrane recovery management, reject-stream optimization, and gradual integration of higher-recovery technologies.

Overall, this study contributes a practical, system-level assessment framework that can be adapted for evaluating water circularity in other energy-intensive industrial facilities. Future work should extend this approach through sensitivity analysis, techno-economic evaluation of staged ZLD implementation, and uncertainty modeling to better support long-term infrastructure planning.

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