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Assessing the Impact of Water Integration on Water Resource Management in Central Asia—A Case Study of Kazakhstani Industry

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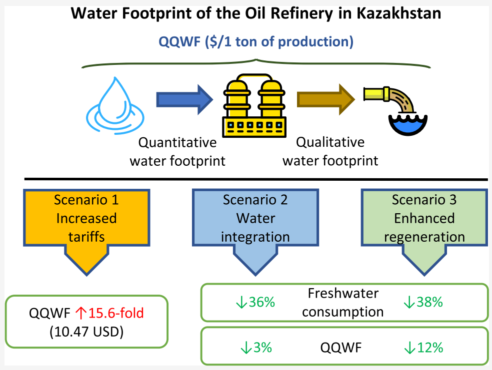

ABSTRACT: This study presents a pioneering attempt to employ a water allocation optimization modeling coupled with a cost-based quantitative–qualitative water footprint (QQWF) approach in a Central Asian country, using the oil refinery industry of Kazakhstan as a representative case study. The QQWF method assesses the costs of water consumption and contamination removal associated with refining one ton of crude oil, considering scenarios of increased tariffs, mathematical optimization, and enhanced water regeneration efficiency. Results show that the state-of-the-art water consumption (32.8%) contributed less to the total QQWF (0.67 USD) than contaminant removal costs (67.2%). Hydrocarbon removal accounted for 71.1% of the qualitative footprint, highlighting the considerable loading of crude oil residues in the wastewater. Scenario simulations revealed a substantial increase (15.6-fold) in the QQWF under increased water tariffs, suggesting the potential of economic instruments for water conservation. Improved efficiency of water regeneration units could achieve a 12% reduction in the QQWF, underlining the importance of wastewater treatment technologies for promoting water reuse within industries. The findings demonstrated the importance of robust, comprehensive incentives to drive the shift toward sustainable water use in industry, particularly within the context of Kazakhstan and Central Asian economies.

KEYWORDS: *water tariffs, water footprint, water integration, oil refinery, environmental resilience, climate change adaptation*

1. INTRODUCTION

Water is an essential natural resource with multiple economic purposes, including agriculture, industry, power generation, and urban and recreational activities. Industrial water use has attracted research attention due to its environmental impact and high consumption rates.[1] As intensive water consumers, industries are particularly vulnerable to climate change-induced water supply disruptions.[2] Given their significance and potential scarcity, water and wastewater are critical resources within the circular economy (CE) principles, such as value retention, waste minimization, and resource efficiency.[3] Global wastewater generation is estimated to be 380 billion cubic meters annually, with projections indicating a 24% increase by 2030 and a 51% by 2050, representing potential available resources for reuse. The potential nutrient recovery from this wastewater could offset 13.4% of the global agricultural demand, including 16.6 Mt of nitrogen, 3.0 Mt of phosphorus, and 6.3 Mt of potassium, while its embedded energy could power 158 million households.[4]

Developing countries face numerous challenges in water resource management due to uneven water resources and differing national water needs These challenges are exacerbated by population growth, environmental degradation, economic development, competing water uses, and climate change.[5] Low tariffs, associated costs, and increasing water consumption hinder the water industry's ability to achieve a high level of circular economy (CE).[6] The UN World Water Development Report has criticized governments worldwide for failing to establish a precise value to water,[7] leading to inefficient water use and slow implementation of water-saving technologies, which are affected by weak tariffication systems.[8]

Aging water infrastructure causes water and energy losses,[9] while limited freshwater renewal rates necessitate a study of consumption, production, and trade patterns within these constraints.[10] Climate change exacerbates these issues, further impacting energy and water demands.[11] Long-term water availability poses risks of stranded assets over the multidecade lifetimes of industrial sites. Despite water management's priorities in national CE implementation programs,[12] systematic barriers still hinder the practical application of process integration.[13]

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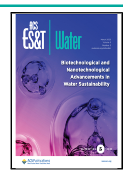

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Research emphasizes countermeasures to mitigate these issues, such as reducing anthropogenic pressure on the environment,[14] addressing water scarcity risks,[15] and promoting efficient water resource use.[16] Effective, powerful tools include Water Integration (WI) and Water Footprint (WF) assessment. WI encompasses a concept aimed at reducing freshwater consumption by reusing wastewater of acceptable quality across sectors,[17] shifting from conventional end-of-pipe waste treatment to sustainable practices focused on pollution prevention and minimization.[18] On the other hand, the WF concept assesses the extent of water use in terms of consumption and contamination, represented in both monetary and volumetric values.[19] Recent advancements in WF methodologies aim to measure water use sustainability by considering the current and future impacts on the environment and economic aspects, especially in industrial applications.[20]

A promising tool, the Quantitative-Qualitative Water Footprint (QQWF) proposed by Jia et al.[15] evaluates the total quantitative water consumption costs and contaminant removal expenses generated during the water use process. This approach monetizes the environmental damage from WF, integrating externalities into decision-making, thus "climate-proofing" water markets for the future.[21] WF and WI concepts converge when evaluating the feasibility of reusing wastewater with specific characteristics, which can be combined with the Water Footprint Pinch Analysis (WFPA) technique.[22] The WFPA integrates flow rate and contaminant mass load balances, coproduct conversion (e.g., biofuel, nutrients, etc.), and process economics into a single model, optimizing water use and minimizing WF across various industries worldwide. Examples demonstrate its effectiveness in the application of pinch analysis in the Indian power sector[23] to address resource conservation problems and optimize cost and WF. Similarly, a graphical WFPA technique applied to the coal-to-methanol process achieved a significant 16% water saving.[22]

Furthermore, water pinch analysis has successfully optimized the water network and reduced blue and gray WF in ethanol industrial production.[24] Tan et al.[25] utilized graphical pinch analysis to identify WF limitations, focusing on constraints in biofuel production systems and providing valuable insights for biofuel crop cultivation planning.[26] The case-oriented study has shown the WF of one brick was 2.02 L, with a 15.6% WF reduction through direct reuse/recycling and a notable 80.4% decrease through water regeneration for brick production.[27] Focusing on minimizing WF by reducing emissions and freshwater abstraction can offer valuable insights for decision-makers evaluating the efficiency of circular water use and its economic implementation benefits.

A critical research gap regarding water integration and WF studies remains in Kazakhstan and Central Asia. Water stress poses severe economic and environmental challenges in the region.[28] The current research primarily addresses agricultural impacts while neglecting the industrial domain, exemplified by Zholdayakova et al.[29] study on WF for hydrogen production. To the authors' knowledge, investigations outside agriculture are limited, highlighting a need for more research on WF reduction in Central Asia industries focused on implementing water-saving techniques. This gap hinders the development of sustainable water management strategies. Therefore, the WFPA approach can contribute to national environmental goals and promote responsible water stewardship.

This research aims to bridge this gap by being the first known study to investigate the opportunities for industrial water use, implying the combined water integration and WF approaches in Kazakhstan and Central Asia. As a case study, this work offers valuable insights to support the transition toward a CE within the regional industrial sector by focusing on an oil refinery in Kazakhstan's Pavlodar region. The specific objectives are to (1) assess the WF of the oil refining process and (2) evaluate the impact of WI through mathematical optimization tools on water use. Additionally, the research explored potential improvements by simulating scenarios with increased water tariffs and enhanced water regeneration unit performance.

2. METHODS

2.1. Building a Water Utilization Network via Water Integration. The water integration technique measures wastewater flow generation, the water consumption index, water reuse, recycling, recovery, and contaminants mass transfer within the water-using processes. This comprehensive approach provides a holistic understanding of water usage and management within a system, facilitating the identification of inefficiencies and opportunities for improvement.

In this case study, water integration was implemented using the adjusted Model for Optimal Design of Water Networks (MODWN) approach.[30] This mathematical optimization framework holistically minimizes freshwater consumption and wastewater generation in systems involving multiple contaminants. The MODWN approach simultaneously evaluates various water strategies to build a minimum water utilization network (MWN). Guided by the water management hierarchy, the MWN considers all conceivable methods to reduce freshwater usage through elimination, reduction, reuse, outsourcing, and regeneration. The allocation model was executed using GAMS Studio software (Release: 45.7.0).

The objective function of this work can be defined either the minimization of freshwater consumption or wastewater generation, as provided in eq 1:

$$\min \sum_j \mathrm{Fw}_j \text{ or } \min \sum_i \mathrm{WW}_i \tag{1}$$

where Fw_j is the fresh water supplied to demand j and WW_i is the unused portion of water source i (waste).

For each water-using operation, the water demand (B_j), can be supplied through multiple sources: fresh water, outsourced resources, reused/recycled water, or regenerated water from a regeneration unit. Similarly, generated wastewater at the water source (A_i), can follow several pathways: direct discharge to the end-of-pipe treatment, reuse in the same or different processes, or partial treatment in the regeneration unit prior to reused/recycled. In this case, the superstructure allows for every possible configuration of a water-using network. The water balance for each demand B_j, and each source A_i is represented by eqs 2and 3:

$$\mathrm{Fw}_j + \sum_i F_{i,j} + \sum_r F_{r,j} = B_j \quad \forall\, j \in J \tag{2}$$

$$\mathrm{WW}_i + \sum_j F_{i,j} + \sum_r F_{i,r} = A_i \quad \forall\, i \in I \tag{3}$$

where $F_{i,j}$ is the water flow rate from source i to demand j; $F_{r,j}$ is the water flow rate from regeneration unit r to demand j; $F_{i,j}$ is the water flow rate from source i to demand j; and $F_{i,r}$ is the water flow rate from source i to regeneration unit r.

The selection of water minimization schemes is based on the assurance that only one scheme can be chosen at a time. Binary

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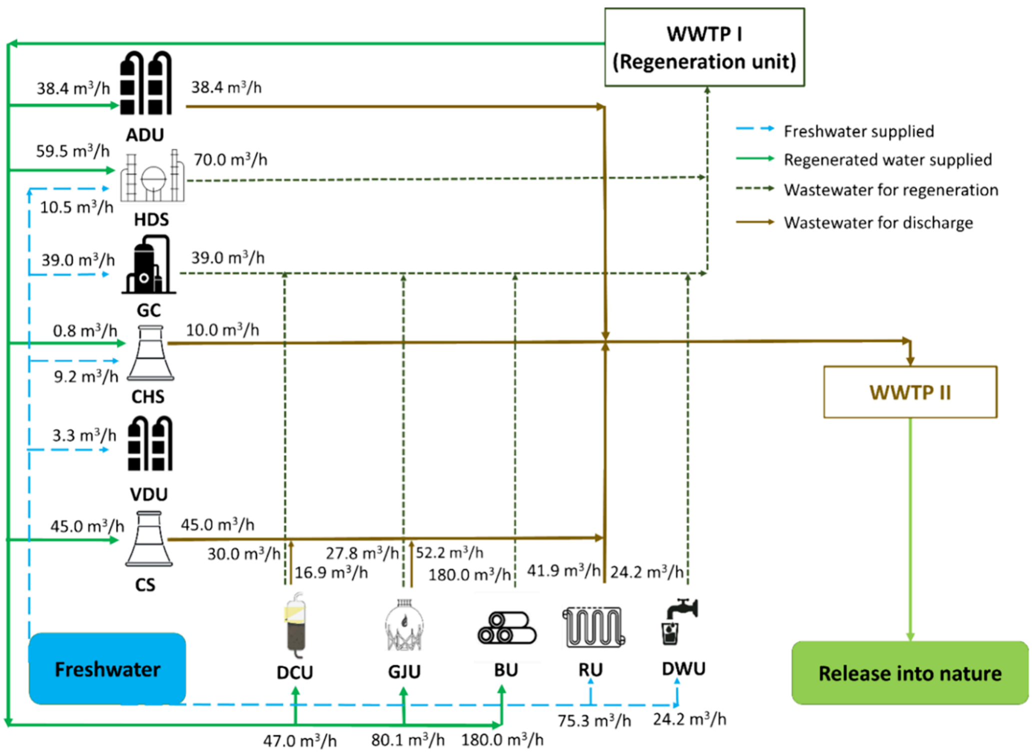

Figure 1. Water use scheme of the studied refinery under the *Base Scenario (0)*.

variables $X_{j,e}$, $X_{j,re}$, and $X_{j,o}$ (in eq 4) are introduced to represent the water minimization options of elimination, reduction, or original operation, respectively:

$$\sum_{e} X_{j,e} + \sum_{re} X_{j,re} + \sum_{o} X_{j,o} = 1 \quad \forall j \in J \tag{4}$$

2.2. Quantitative−Qualitative Water Footprint Assessment. The QQWF, developed by Jia et al.,[15] is utilized in this study as an intuitive and comprehensive tool for monitoring and managing water use in industries. It incorporates both the total cost of water quantity consumption, and the cost associated with contaminant removal produced generated during industrial processes. The QQWF comprises two subindicators: Quantitative WF (WF_{qt}) and Qualitative WF (WF_{ql}), which address quantity and quality aspects of water use, encompassing a range of contaminants. Unlike existing WF indicators, the QQWF assesses the cost-based comparisons of water quality and quantity footprints across diverse water processes. This capability enables users and managers to identify critical water-consuming sectors and pinpoint bottlenecks within the water use cycle (i.e., excessive consumption or pollution generation). The QQWF offers several advantages, including (i) the calculation of the current cash flow of water use, (ii) the provision of more accurate information to guide water management decisions, and (iii) the assessment of the environmental impact of human activities on the water recourses within established boundaries.

Equations 5−8 form the basis for calculating the QQWF. The original equation was modified by replacing $F_{dc,j}$ with $F_{rec,j}$ in eq 6 to evaluate the environmental impact of water pollution while considering the efficiency of the regeneration unit.

$$\begin{aligned} WF_{qt,j} = {} & EC_{fs} \times F_{fs,j} + EC_{re} \times (F_{re,k\text{-}j} - F_{re,j\text{-}n}) \\ & - EC_{fs} \times F_{rec,j} + WDF_{dc} \times F_{dc,j} \end{aligned} \tag{5}$$

$$WF_{ql,j} = \sum_{i} (F_{rec,j} \times C_{dc,i,j} - F_{fs,j} \times C_{fs,i,j}) \times TC_{i} \tag{6}$$

$$QQWF_{j} = WF_{qt,j} + WF_{ql,j} \tag{7}$$

$$QQFW = \sum_{j} WF_{qt\text{-}ql,j} \tag{8}$$

where EC_{fs} is the unit cost of freshwater, USD/m^3; EC_{re} is the unit cost of reused water, USD/m^3; WDF_{dc} is the wastewater discharge fee, USD/m^3; $F_{fs,j}$ is the volume of input freshwater to water-using unit j, m^3/t product; $F_{dc,j}$ is the volume of water discharged from water-using unit j, m^3/t product; $F_{re,j\text{-}n}$ is the volume of water reused from water-using unit j to n, m^3/t product; $F_{re,k\text{-}j}$ is the volume of reused water input to water-using unit j, m^3/t product; $F_{rec,j}$ is the volume of water discharged from water-using unit j after treatment to environment, m^3/t product; TC_i is the cost of treating contaminant i in a centralized wastewater treatment plant, USD/kg contaminant i; $C_{dc,i,j}$ is the concentration of pollutant i in the discharge flow from water-using unit j, mg/L; $C_{fs,i,j}$ is the concentration of pollutant i in the input freshwater to water-using unit j, mg/L; $WF_{ql,j}$ is the Qualitative Water Footprint of the water using unit j, USD/t product; and $WF_{qt,j}$ is the Quantitative Water Footprint of the water using unit j, USD/t product.

2.3. Case Study. The oil refinery industry in Kazakhstan consumed 77.8 million m^3 of water in 2016, reusing only 3.5 million m^3, with the remainder discharged into the environment. Despite the efforts of both the government and the industry to control the pollution, three oil refinery factories in Kazakhstan remain among the largest sources of water contamination.[31] The wastewater generated primarily consists of salty, unprocessed heavy oil−water emulsions, which pose significant challenges for hydrocarbon removal. The current

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approach employed by refineries in Kazakhstan relies predominantly on the activated sludge biological treatment method, which is ineffective for two main reasons. First, the low biodegradability of the petroleum hydrocarbons in the wastewater limits the treatment's effectiveness. Second, the high salinity and toxicity of the wastewater inhibit biomass efficiency within the treatment system. In contrast, refineries in other countries utilize advanced techniques at each treatment stage: preliminary, secondary, and post- (or polishing) treatment. Such comprehensive practices are rarely implemented in Kazakhstan's refineries, highlighting the urgent need for significant improvements in their wastewater management practices.[16]

This study focuses on an oil refinery located in the Pavlodar region of northern Kazakhstan. The historical contamination and legislative loopholes have resulted in severe contamination of the recipient pond for wastewater from the refinery, leading to extended groundwater pollution, which has likely existed for decades and spread out over a kilometer-scale.[16] The refinery currently employs an outdated wastewater treatment system with two parallel treatment lines. While both lines follow the same basic treatment steps (as detailed in ref14), they operate on separate streams based on the contaminant load. The first line treats "conditionally clean" effluents, which are designated for reuse after treatment in the "regeneration unit" (Figure 1). The second line handles highly contaminated wastewater, which is discharged into the receiving pond after treatment using basic mechanical and biological methods.

The water use scheme (Figure 1) is based on the report provided by the refinery.[32] It assumes the maximum loading of the industrial process, corresponding to over 6 Mt/y (or 685 t/h) of crude oil refined. According to the report, processing units utilize freshwater from a local supplier and treated wastewater, which is defined as regenerated water. In this case study, freshwater is considered as the primary source. Alternative water sources, such as pretreated water from other industries, are excluded from the analysis. The feasibility and impact of incorporating alternative water sources will be explored in future studies. The projected flows of freshwater and regenerated water supplied are 161.5 m^3/h and 450.8 m^3/h, respectively. The refinery generates 204.4 m^3/h of wastewater, which is subsequently treated and discharged into the environment. The industry provided detailed data on water quality throughout 2022, including average concentrations of specific contaminants in treated wastewater, crucial for WF assessment and water integration. Table 1 presents the refinery's processing units' water use data, including inputs and outputs.

Three key contaminants were selected as indicators to assess water quality and potential environmental impact: total petroleum hydrocarbons (TPH), ammonia, and sulfides. TPH and H_2S are consistently monitored in both processed water and wastewater streams within crude oil refining and have remained unchanged throughout the history of water integration in this sector. Ammonia served as an emerging contaminant for the studied refinery,[14] allowing a more comprehensive assessment of potential environmental and operational challenges.

2.4. Scenarios Selection. This work raises three crucial weaknesses in the Central Asian region, focusing on the Kazakhstani industrial water sector, presented through three corresponding scenarios: (i) the reflection of the water tariff system, (ii) the reflection of the absence of a water minimization approach, and (iii) the reflection of outdated infrastructure.

2.4.1. Scenario 1. Impact of Increased Tariffs. The first scenario examines the issue of inefficient tariff structures within the water sector. The current water tariff system in Kazakhstan has been criticized for its lack of sustainability, as enterprises that consume large volumes receive preferential rates (approximately 0.04−0.10 USD per m^3),[6] among the lowest globally.[33] To further explore this issue, this scenario introduces an "increased tariff" model to compare Kazakhstan's very low tariffs with those of an advanced developed country (in this case - China). This comparison examines the inefficiencies in Kazakhstan's tariff structures and their impact on water sector performance.

Data acquisition for water-related costs encompassed three categories: water supply, wastewater discharge, and contaminant removal (Table 2). The costs are presented in USD (assuming 1 USD ≈ 470 KZT based on the rate in the national budget at the time of this study).

Water supply pricing data were obtained from industry representatives upon special request. Wastewater discharge fees were gathered from specific inquiries and publicly available sources.[34] It is suggested that the bulk unit cost of contaminant

Table 1. Characteristics of Water Demand and Contamination Generated by Industrial Units of the Studied Refinery per Ton of Crude Oil Refined

Unit	Unit abbreviation	Flow rate of supplied water (m^3/h)	Contaminants (mg/L)		
			TPH	NH3-N	S2-S
Atmospheric distillation	ADU	38.4	1,000	4,500	5,000
Hydrotreating	HDS	70	300	4,378	4,870
Gas compression	GC	39	800	4,500	5,000
Chimney stack 1	CHS	10	200	30	20
Vacuum distillation	VDU	3.3	-	-	-
Chimney stack 2	CS	45	188	30	20
Delayed coking unit	DCU	47	200	30	20
Gas junction	GJU	80.1	65	30	20
Bitumen	BU	180	3,000	30	20
Industrial recycling unit	RU	75.3	25	30	20
Drinking water	DWU	24.2	5	30	20

Table 2. Unit Cost of Water Supply, Discharge, and Contaminant Removal

Item	Cost 1 (*Base scenario*)	Cost 2 (*Increased scenario*)
Water supply	USD/m^3	
Freshwater	0.05	0.65
Regenerated water	0.27	3.51
Wastewater discharge	0.27	3.51
Contaminant treatment	USD/kg	
TPH	3.90	64.74
NH3-N	0.50	8.30
S2−S	0.015	0.25

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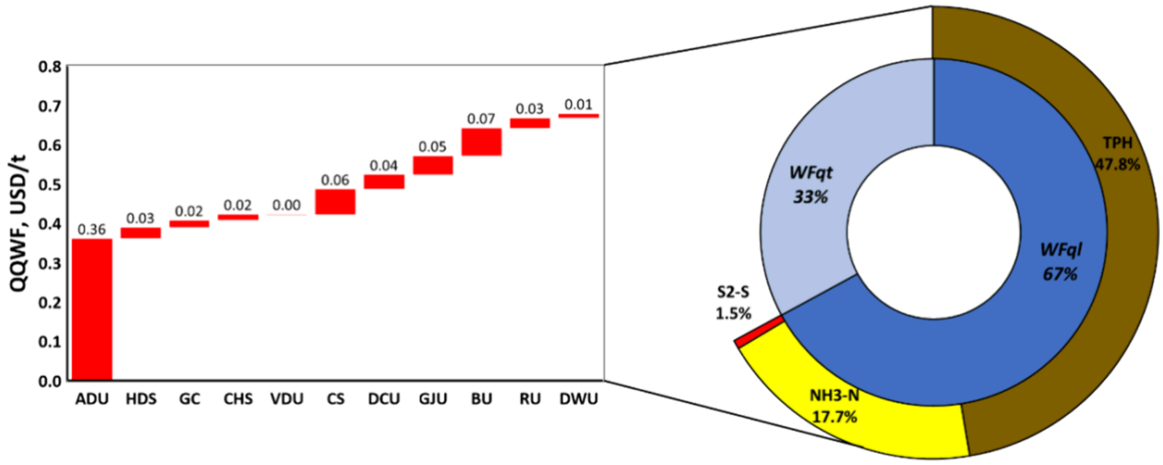

Figure 2. Breakdown of the QQWF of refining 1 ton of crude oil under *Scenario 0*: distribution across industrial units, quantitative and qualitative components, and selected contaminants.

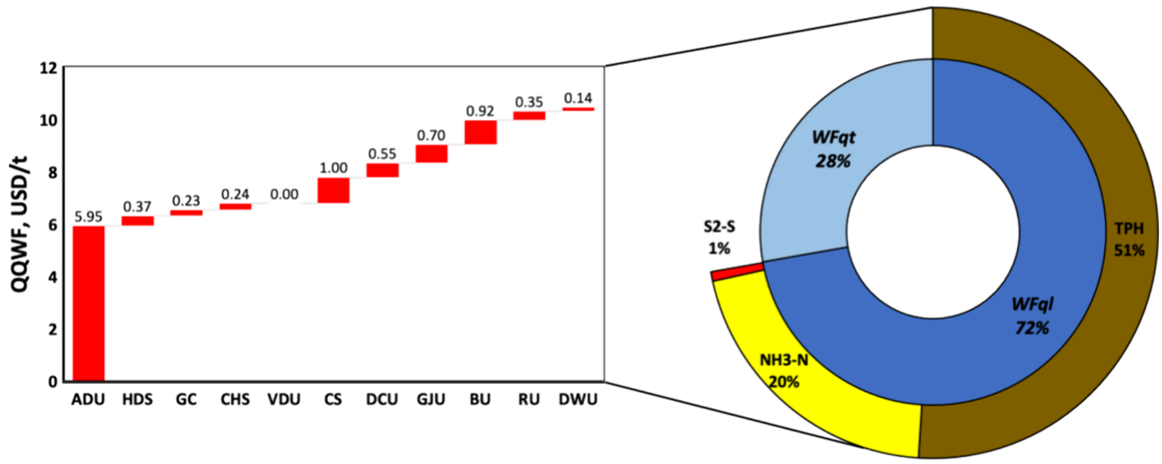

Figure 3. Breakdown of the QQWF of refining 1 ton of crude oil under *Scenario 1*: distribution across industrial units, quantitative and qualitative components, and selected contaminants.

removal be calculated using a mass-based distribution method.[15] The tariffs in the increased fees scenario were adjusted based on the methodology outlined by Jia et al.,[15] utilizing data from the Chinese water utility Jinan Water Group for 2020. These adjustments accounted for the costs of freshwater supply and ammonia removal. Costs associated with regenerated water supply, wastewater treatment, and removing TPH and sulfides were interpolated using the corresponding ratios. The other two scenarios address the infrastructural challenges commonly observed in industries across the studied region.

2.4.2. Scenario 2. Minimizing Freshwater Consumption. The second scenario emphasizes Kazakhstan and Central Asia's lack of water integration studies. The potential for water saving and reuse remains underexplored, as comprehensive assessments of water supply measures have not yet been conducted. Two options can be considered as the objective functions for the water pinch analysis: minimization of freshwater abstraction or wastewater generation. The selection of the option depends on achieving the best performance in the subsequent QQWF assessment. Thus, the minimization of freshwater withdraw is chosen as the targeted function.

2.4.3. Scenario 3. Enhanced Regeneration Efficiency. The third scenario focuses on another global critical weakness—the limited efficiency of existing infrastructure. Successfully implementing the CE approach requires feasible, innovative technologies and infrastructure that align with efficient legislation and standards. The factor "poor or obsolete conditions of the water infrastructure" has been identified as the most influential factor in the industrial water management systems of the region concerning the implementation of water conservation principles in industries.[6] The wastewater and regeneration units in the studied refinery are outdated and inefficient, indicating significant potential for improvement in their performance and the production of regenerated water. This scenario investigates the impact of enhanced wastewater treatment and the efficiency of the regeneration unit. The focus is on upgrading the regeneration unit and tightening the discharge limits for the quality of regenerated water by eliminating hydrocarbons and sulfides and decreasing ammonia to 10 mg/L.

3. RESULTS

3.1. QQWF Assessment for Scenario 0 and 1: Base Scenario and Increased Tariffs. A cost-based QQWF assessment was performed for refining one ton of crude oil under two scenarios: base scenario (*Scenario 0*) and increased tariffs (*Scenario 1*).

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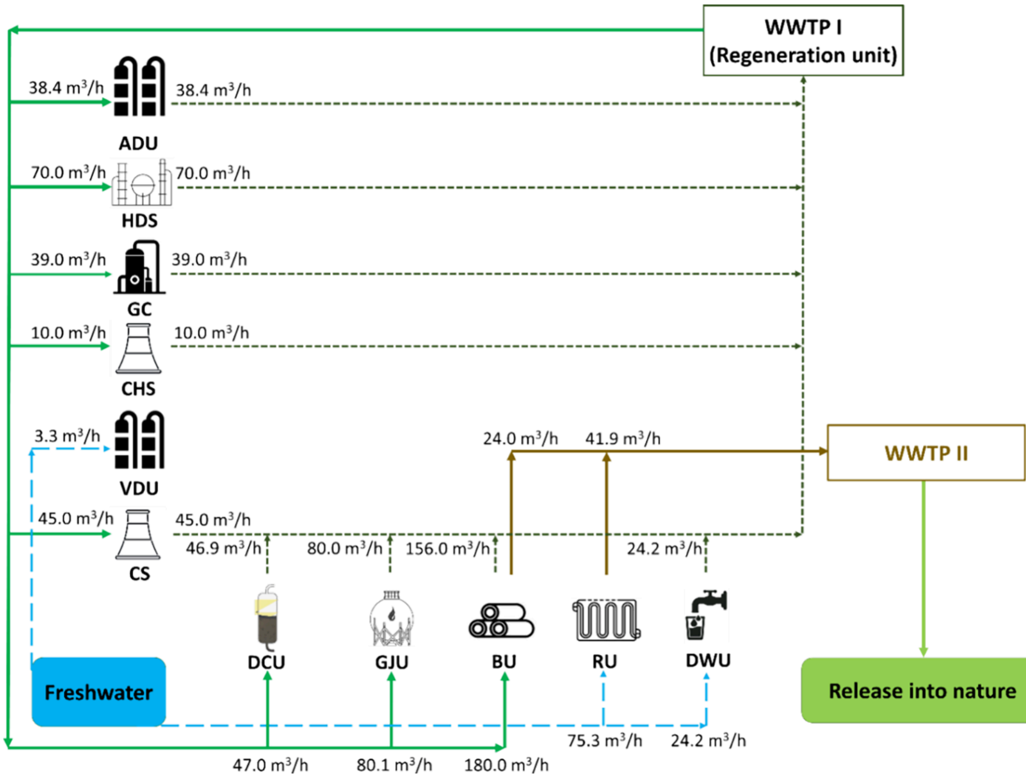

Figure 4. Water use scheme of the studied refinery under *Scenario 2.*

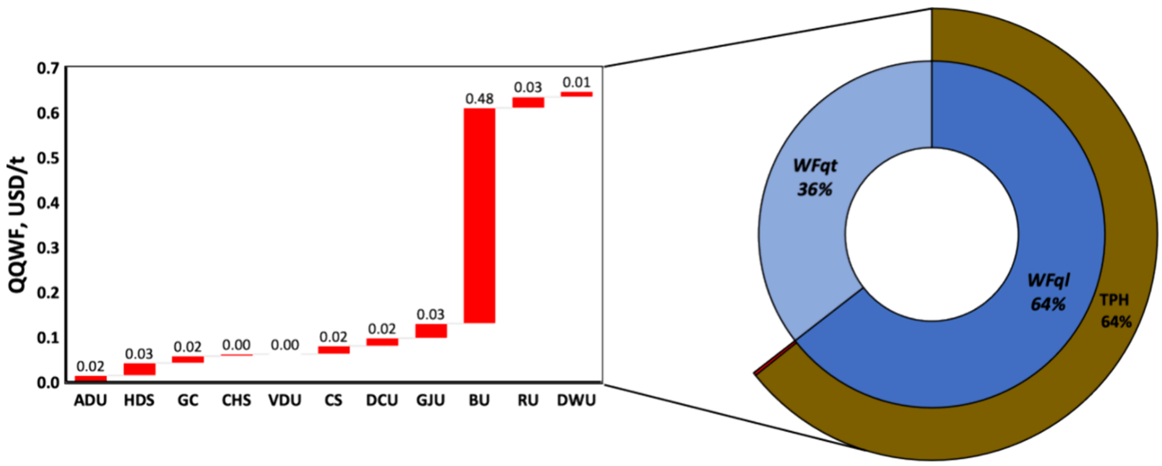

Figure 5. Breakdown of the QQWF of refining 1 ton of crude oil under *Scenario 2*: distribution across industrial units, quantitative and qualitative components, and selected contaminants.

3.1.1. Scenario 0. Base Scenario. Figure 2 illustrates the breakdown of the quantitative and qualitative footprints for the base scenario. The results indicated that the total QQWF amounted to 0.67 USD per ton of crude oil refined. This value comprised a water consumption cost of 0.22 USD and a contaminant removal cost of 0.45 USD, representing 32.8% and 67.2% of the total QQWF, respectively. This finding reflects the critical need to prioritize contamination reduction strategies over solely minimizing freshwater consumption.

Among industrial units, atmospheric distillation emerged as the primary contributor to the overall footprint, responsible for over half (53.7%) of the total QQWF. TPH dominated qualitative WF, accounting for 71.1%, indicating substantial contamination from heavily degradable crude oil residues. Ammonia contributed 28.9% (0.13 USD) of the qualitative footprint.

The topping unit, where crude oil is separated into various straight-run fractions via atmospheric or vacuum towers, was pinpointed as the primary source of contamination. The steam stripping and corrosion processes control employed in fractionation towers during distillation were found to cause severe contamination. Additionally, the refining of heavy oil residues (bitumen, delayed coking, and gas junction units) contributed a substantial share (0.16 USD or 23.9%) to the total QQWF. Furthermore, chimney stacks significantly contributed to the total QQWF, accounting for 0.08 USD (11.9%). These findings highlight the high environmental impact of the refinery, reflected in its substantial contaminant load and elevated WF.

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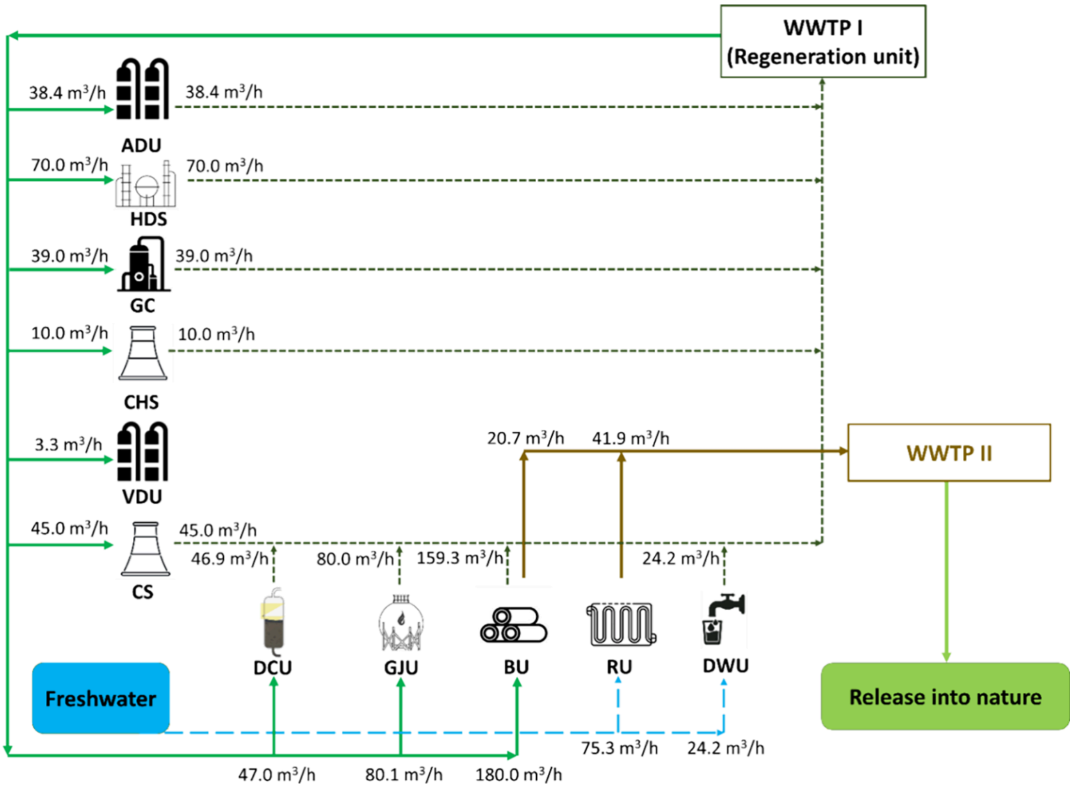

Figure 6. Water use scheme of the studied refinery under *Scenario 3.*

3.1.2. Scenario 1. Impact of Increased Tariffs. *Scenario 1*, which simulates the impact of increased tariffs, resulted in a significant 15.6-fold rise in the total QQWF, reaching 10.47 USD (Figure 3). This increase is attributed to 2.91 USD (27.8%) for quantitative WF and 7.56 USD (72.2%) for qualitative WF. Notably, the ratio between these two components shifted slightly, with the impact of contaminant removal costs becoming even more prominent.

Despite the overall increase in costs, the relative contributions of individual industrial units and selected contaminants remained essentially unchanged. This suggests that while increased tariffs primarily affect the overall cost, they do not significantly alter the underlying sources of water consumption and contamination within the refinery.

3.2. QQWF Assessment for Scenario 2 and 3: Mathematical Optimization and Enhanced Regeneration Efficiency. This section explores the impact of water minimization strategies on the QQWF. Two optimization approaches were implemented, with the objective function designed to minimize either wastewater or freshwater consumption.

3.2.1. Scenario 2. Minimizing Freshwater Consumption. The minimization of freshwater abstraction was identified as the most effective strategy for decreasing the overall WF, demonstrating the best performance in the QQWF assessment. The water flow scheme for this scenario, which avoided direct water reuse, is presented in Figure 4.

The simulation modeled freshwater and regenerated supply flows of 102.8 and 509.5 m^3/h, respectively. The wastewater generation rate was 65.9 m^3/h, undergoing final treatment before discharge into the environment. Compared to the base scenario, *Scenario 2* significantly reduced freshwater consumption (36.3%) and wastewater generation (67.8%). This optimization resulted in a freshwater consumption rate of 0.15 m^3 per ton of crude oil refined.

However, the total QQWF with the optimized water flows remained relatively unchanged at 0.65 USD (Figure 5). This suggests that contaminant removal costs remained dominant despite a significant reduction in water consumption. The footprint for atmospheric distillation and chimney stack units was nearly eliminated, reaching 0.02 USD. Conversely, the footprint of bitumen production unit increased to 0.48 USD, contributing 73.8% to the total QQWF.

The increased footprint of the bitumen production unit can be attributed to the complexities and costs associated with hydrocarbon removal processes. While other contaminants were effectively treated, it is critical to address hydrocarbons more cost-efficiently. These findings emphasize the importance of developing refined treatment strategies for specific contaminants to achieve a more balanced and cost-effective environmental footprint across the entire industrial process.

3.2.2. Scenario 3. Enhanced Regeneration Efficiency. Similar to *Scenario 2*, the objective function in Scenario 3 focused on the minimization of freshwater consumption (Figure 6).

The modeled flow rates of freshwater and supplied regenerated water were 99.5 m^3/h and 512.8 m^3/h, respectively (Figure 6). The generated wastewater, totaling 62.6 m^3/h, was directed for final treatment before discharge into the environment. Compared to the base scenario, this scenario achieved significant reductions in both freshwater consumption (38.4%) and wastewater generation (69.4%). The enhanced efficiency of the regeneration unit had minimal impact on the freshwater consumption rate per ton of crude oil refined (0.15 m^3), relative to the mathematical optimization. The only unit that eliminated freshwater use was the vacuum

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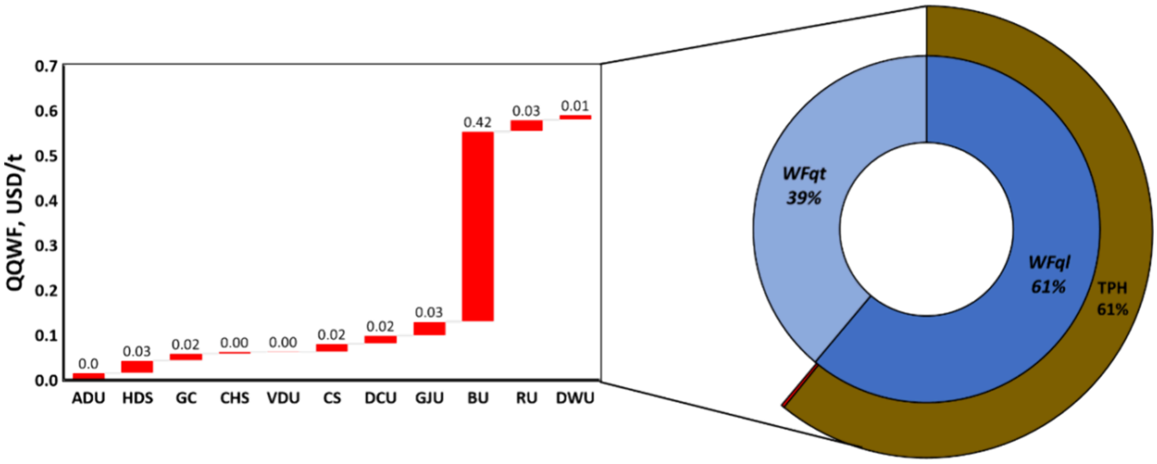

Figure 7. Breakdown of the QQWF of refining 1 ton of crude oil under *Scenario 3*: distribution across industrial units, quantitative and qualitative components, and selected contaminants.

Table 3. Results of the Mathematical Optimization and Enhanced Water Regeneration Unit Implementation

Scenarios	Freshwater consumption (m^3/h)	Wastewater generation (m^3/h)	QQWF (USD/t)	WF_{qt} (USD/t)	WF_{ql} (USD/t)
Base scenario	161.5	204.4	0.67	0.22	0.45
Scenario 2	−36.3%	−67.8%	−3.0%	+4.5%	−6.7%
Scenario 3	−38.4%	−69.4%	−11.9%	+4.5%	−20%

distillation unit, which maintained a flow rate of 3.3 m^3/h in both scenarios.

However, the total QQWF decreased by 12%, reaching 0.59 USD compared to the base scenario (Figure 7). This reduction was primarily attributed to a total decrease in the qualitative footprint of the bitumen production unit. Nevertheless, not the whole flow was sent for regeneration.

Additionally, the quality of regenerated water needs to be improved to meet the standards required for industrial recycling and drinking water units, which still require freshwater for industrial needs.

4. DISCUSSION

This section discusses how the results of this study on WF optimization strategies can accelerate the shift toward sustainable water management within the industrial sector in developing countries. It considers the policy implications of the findings, addresses data challenges and limitations, and identifies further steps needed.

4.1. Water Consumption Efficiency of the Studied Refinery. The study's outcomes highlight the significant potential for environmental improvement through proposed water management strategies (Table 3). Implementation of the modeled scenarios could result in substantial reductions in freshwater withdrawal (513,550−543,260 m^3 per year) and wastewater generation (1,197,358−1,242,637 m^3 per year) compared to current base *Scenario 0*. These reductions directly align with national sustainability goals, such as the "Green Kazakhstan" program, which targets a 24% decrease in freshwater intake (from 5.8 to 4.4 km^3) by 2025.[35]

The potential cost savings associated with the total QQWF reduction are also noteworthy. *Scenario 2* (optimized water network) could achieve annual savings exceeding 120,000 USD, while *Scenario 3* (enhanced regeneration efficiency) offers greater potential savings exceeding 478,000 USD. These economic benefits provide a compelling incentive for refineries to embrace water management strategies.

The *Base Scenario* for the studied refinery demonstrates a freshwater consumption rate of 0.24 m^3 per ton of refined crude oil, which appears favorable compared to established industry practices. For example, U.S. refineries' water usage is estimated to range between 1.55 and 2.14 m^3 of water[36] or 1.0−1.9 m^3 per m^3 of crude oil with a median of 1.5 m^3.[37] Previous research showed similar refinery water consumption rates of 1.0 L water per 1.0 L of refined crude oil but with a much wider range of 0−7.2 L water per L of refined crude oil.[38] A case study in Thailand reported consuming 40 t/h of process water at a crude throughput of 8 Mt/y. While direct comparison is challenging due to unit differences, this translates to a water consumption rate potentially exceeding 0.5 m^3/t. Values as low as 0.5 m^3 per ton of crude oil have been achieved within European refineries.[39]

The findings suggest that the studied refinery's water consumption falls within the lower range of reported values for global refineries, indicating efficient water management practices compared to the broader industry. However, further optimization opportunities might exist, as evidenced by even lower water consumption rates in certain European refineries.

Most research on WI applications in the oil refinery sector worldwide has been dedicated to developing new water pinch models. The fundamental development of the research direction was done by Wang and Smith.[40] While their study focused on improving algorithms and representation for water integration, they also highlighted the importance of regeneration unit implementation and the potential for noncost-driven optimization objectives, such as water reuse for WF reduction. This approach is extremely relevant nowadays for water-scarce regions. Quaglia et al.[41] conducted the only known research where WF minimization was the objective function in water integration in oil refineries. Their case study demonstrated significant reductions in total annualized cost (21.8%) and WF (45.3%) through wastewater treatment and reuse strategies. Similarly, Santos et al.[42] reported a 20% decrease in raw water intake and a 70% in the effluent volume disposed of in the soil,

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reducing the WF and enhancing the petrochemical industry's sustainability. These advancements collectively demonstrate the evolution of the landscape of water integration within the oil refinery sector, emphasizing a pivot toward addressing WF minimization as a central objective, thereby contributing to enhanced sustainability and resource efficiency within the industry.

Comparing the available sources for WF assessment of crude oil refining reveals inconsistencies. Refineries exhibit substantial variations in both water flow rates and wastewater contamination levels, complicating estimates of freshwater demand and making replication of a standard water network design challenging.[41] Several factors contribute to this inconsistency, including internal water management practices and wastewater treatment systems, the level of implementation of Best Available Techniques (BAT) for water conservation and pollution control, and the integration of CE principles.[13] Gerbens-Leenes et al.[43] quantified the WF of oil refining at 0.09 m^3/GJ. Water consumption rates for gasoline production ranged from 2.8 to 6.6 L of water per L of gasoline for over 90% of crude oil, depending on refining processes and volume expansion when crude is converted into refinery products.[44]

4.2. Limitations. This study highlights the systematic limitations of industrial water management in Kazakhstan,[6] particularly within the context of a refinery. The lack of proper water consumption and water quality measurement facilities poses significant challenges for monitoring water use, identifying water losses, and implementing effective water-saving solutions.

Addressing the limitations requires investment in measurement infrastructure. Equipping industries with flowmeters and measurement points is crucial for real-time data collection on water consumption and contaminant levels in wastewater streams. This data will enable accurate monitoring, loss identification, and targeted interventions. To mitigate these limitations, the study adopted several strategies to enhance data robustness, including the use of real-time flow data from Alva-Argaez et al.[45] and Al-Redhwan et al.,[46] which considered factors such as similarity of refinery configurations and crude oil types and comparability of wastewater treatment processes. Additionally, clearly stating the source of data obtained from Radelyuk et al.[14] regarding the characteristics of the regeneration unit and regenerated water quality ensures consistency with other aspects of the investigated refinery. By incorporating data from these sources, the study aimed to enhance the comprehensiveness and accuracy of its analysis, albeit within the constraints of available information. However, it is crucial to acknowledge that the reliance on secondary data sources may introduce uncertainties and limitations to the study's findings. For instance, the characteristics of the regeneration unit and the quality of regenerated water may vary across different contexts and timeframes, potentially impacting the robustness of the analysis.

Another limitation was restricted access to detailed contamination treatment cost data, calculation complexities, and the absence of independent and alternative expert analysis. It highlights the need for greater transparency and collaboration among stakeholders in the industrial water management domain. Company confidentiality policies limit access to detailed cost breakdowns for specific treatment processes. Accurately calculating treatment costs requires considering various factors such as chemical costs, energy consumption, and equipment depreciation. Efforts to improve data accessibility and quality and foster interdisciplinary collaborations between academia, industry, and government bodies are essential for overcoming these limitations and advancing understanding of sustainable water management practices in industrial settings. Collaboration with researchers and independent experts can provide access to detailed contamination treatment cost data, which is essential for accurate cost analysis and informed decision-making regarding water treatment technologies. Therefore, relying on approximate values from factory normative documentation government bodies[47] and factory documentation[32] introduces potential biases or inaccuracies. Government data might not reflect the actual costs incurred by the refinery, and industry documents might not consider all relevant cost factors.

4.3. Policy Implications and Recommendations for Sustainable Industrial Water Management. This study highlights a gap between Kazakhstan's aspirations for a green economy and the lack of practical adoption of green technologies across industries. While the government has made strides in formulating policies and legal frameworks, recent shortcomings in implementing effective mechanisms, such as financial incentives and promotional tools, have hindered the widespread adoption of green technologies across all sectors.[31]

A pivotal document in this regard is the recently updated Ecological Code, which advocates for the adoption of BAT as the primary driver for enhancing environmental conditions in the midterm and optimizing resource utilization in the long term.[48] The upcoming regulations to be instituted by 2025 provide enterprises, including the studied refinery, sufficient time to align with these new requirements. The requirements should include the reduction of freshwater abstraction, the improvement of wastewater treatment, and the curbing of pollution.[13] Technical guidance and a phased timeline are designed to assist industries in adapting to these measures. Reinvesting collected fees into protective projects further supports environmental goals. Penalties remain low during the transition period, then rise post-2025 for noncompliance, ensuring fairness and economic feasibility. This balanced approach combines "Polluter pays" principle with incentives to foster economic growth, innovation, and global competitiveness, securing long-term benefits for water resources. Notably, most industries, including the studied refinery, are listed among the top 50 polluters in Kazakhstan and are mandated to prioritize BAT implementation.[49] However, concerns exist regarding specific provisions, such as exemptions for enterprises from BAT guidelines concerning environmental-related fees.[50] Additionally, to ensure the effectiveness of sector-specific BAT guidelines under development,[13] including a comprehensive list of cutting-edge treatment techniques beyond the BAT requirements is crucial. Subsidy programs for water reuse play a crucial role in promoting sustainable water management practices worldwide.[51] Governments and corporations can incentivize industries to adopt industrial water recycling technologies and practices through financial support, particularly in light of forecasted water stress. These measures can lower the initial investment required for water treatment technologies, making it more feasible for industries to implement water reuse systems.[52] However, challenges exist, including the need for industry-wide commitment and the potential for dependency on financial support. Balancing these factors is essential for sustainable water management in industrial sectors.[53]

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Additionally, these guidelines should consider techniques and technologies with lower environmental footprints throughout their lifecycle[54] and implement cutting-edge technologies suitable for different industry sizes and financial capabilities. This could involve tiered approaches with varying levels of stringency. The optimization strategies proposed in this study, resulting in a reduced total QQWF for the refinery, offer a viable model for BAT compliance and enhanced environmental resilience across similar industries.

Furthermore, this study confirms that the undervaluation of water resources in Kazakhstan, reflected by low tariffs, presents a significant obstacle to implementing CE principles in water management.[6] Despite these low tariffs, the major investments for improving the water distribution network primarily rely on governmental subsidies. This reliance presents a significant obstacle for industries seeking to adopt advanced water-saving techniques, as such changes have no incentive. The problem lies not solely in the tariff system itself but in the infrastructure's outdated physical and operational conditions and the inertia associated with the capital stock. This obsolescence results in substantial water losses and inefficient wastewater treatment, posing immediate and long-term risks to human health and ecosystems due to water pollution. Furthermore, some Kazakhstani industries resist even the current low water tariffs, criticizing the methodologies employed for their determination. Such resistance exists despite the risk posed to future profits by climate change and water stress. This lack of appreciation of such risks highlights the urgent need to foster positive changes in pursuit of environmental sustainability. Recent studies suggest that volumetric variable pricing mechanisms are among the most effective strategies for improving water-use efficiency[55] and promoting the adoption of circular economy principles.[56] Moreover, research indicates that merely announcing tariff increases can often have a greater impact on reducing water consumption than implementing higher water prices.[57] While low tariffs and accessibility to cheap energy resources attract investments, they ultimately strain environmental resilience.[58] This study delves into the impact of water pricing on water management practices, revealing that increased tariffs can lead to notable shifts in freshwater consumption and wastewater generation. Policymakers should consider adjusting water pricing structures to reflect the actual value of water and incentivize industries to adopt water-saving technologies, WI, and material recovery processes. A tiered pricing structure with higher tariffs for excessive water usage could serve as an effective strategy.

These policy gaps should be addressed by facilitating partnerships between government agencies, industries, and research institutions to promote knowledge sharing, technology transfer, and joint investment in innovative water management solutions. A comprehensive review and update of the regulatory framework for industrial water management, aligned with international best practices, is required. Adopting and promoting these measures will support Kazakhstan in achieving a lower overall WF, ensuring the long-term availability of water resources, protecting the environment, and contributing to a more sustainable future. Finally, the formation of a grand coalition of finite regional actors, including other industries and stakeholders with authority, can facilitate the implementation of water recycling in eco-industrial parks, considering nearby water users as potential water sources and sinks.

5. CONCLUSIONS

This study highlights the multifaceted nature of water integration applications in manufacturing industries of developing economies. The successful implementation has been proved by the employment of the Quantitative-Qualitative Water Footprint (QQWF) assessment. This study represents the first known evaluation of the environmental impact of water pinch analysis in a Central Asian country context, specifically Kazakhstan. The findings provide valuable insights into water management challenges and optimization opportunities for economies facing outdated infrastructure and low water tariffs.

While freshwater consumption remains a critical concern, the analysis indicates that reducing wastewater contamination levels should be prioritized, as indicated by the breakdown of the total QQWF (67.1%). The dominance of total petroleum hydrocarbons within the qualitative footprint (71.1%) emphasizes the need for stricter regulations and advanced treatment technologies for their removal. Furthermore, the economic benefits of water regeneration efficiency improvements (12% QQWF reduction) provide a compelling argument for technology investments. The studied refinery's freshwater consumption rate (0.24 m^3/t) reveals favorable performance compared to global practices. Mathematical optimization simulations demonstrated significant reductions in both freshwater consumption (36.3%) and wastewater generation (67.8%) through optimized water networks. The economic benefits are also noteworthy; enhanced water regeneration efficiency can achieve a 12% reduction in total QQWF, with potential annual cost savings exceeding 120,000 USD for an optimized network and 478,000 USD for improved regeneration.

The case study of Kazakhstan serves as a valuable example for countries facing similar challenges, including water scarcity and outdated industrial water management systems. This research provides empirical evidence and identifies systematic deficiencies in Kazakhstan's industrial water management system. The findings can inform policy decisions and guide the development of water management practices in developing countries addressing water stress, improved water resource safety, and sustainable resource management. Comparison with existing literature highlights the variability in water footprint estimates for oil refining, emphasizing the need for standardized methodologies. Future research should contribute to developing and implementing standardized approaches for accurate and comparable water footprint assessments across different regions and industries.

This study demonstrates the need for policy interventions such as reinforcing environmental fee policies, setting stricter water quality standards, and promoting water reuse through regulation frameworks and economic incentives. These instruments must be sufficiently robust to overcome infrastructural inertia and enable the development of climate-resilient systems. Future research could extend beyond these limits by exploring the integration of renewable energy sources into water treatment processes further to minimize the environmental impact of water management systems. Additionally, developing advanced water treatment technologies for achieving higher regenerated water quality would expand the potential for water reuse within refineries. Finally, conducting cost-benefit analyses for various water management strategies

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across different industrial sectors in Kazakhstan would also provide valuable insights for informed policymaking.

By implementing these recommendations and exploring further research avenues, Kazakhstan and other developing countries can move toward more sustainable water management practices in the refining industry and beyond. This progress would contribute to a cleaner environment, enhanced resource efficiency, and a more sustainable future.

ASSOCIATED CONTENT

Data Availability Statement

Data used in this study can be provided upon a reasonable request.

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Notes

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