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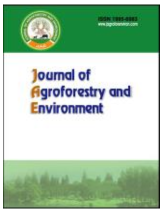

A Systematic Approach in Industrial Water Management: Water Pinch Analysis (WPA)

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Abstract: The global water scarcity issue, which is being intensified (or worsening) due to climate change and rising industrial demand, poses a significant threat to sustainable development. In response to this pressure, water-intensive industries such as petrochemical refining, pulp and paper, and food processing are adopting targets based on the principles of the circular economy and zero liquid discharge. Water Pinch Analysis (WPA) is recognized as one of the most effective systematic methodologies for achieving these objectives. This study provides a comprehensive review of the WPA methodology by synthesizing extensive literature on its theoretical background, historical development and practical application. The methodology has evolved from its origins in mass balance principles to the more holistic approaches that are evident today. The study also underscores certain limitations, including the single-contaminant assumption, steady-state calculations, and the fact that achieving the minimum water target does not always result in the minimum total annualized cost. Despite these limitations, case studies demonstrate the potential of WPA to achieve freshwater savings in industrial applications. It is concluded that, when combined with economic optimization and energy-water-carbon nexus analyses, WPA is a central and proven tool for improving industrial resource efficiency. Consequently, it is recommended that industries implement WPA not merely as a standalone targeting tool but within a holistic Energy-Water-Carbon Nexus framework, prioritizing designs that balance theoretical freshwater minimization with realistic economic constraints to ensure long-term viability.

Keywords: Water Pinch Analysis (WPA); Water minimization; Industrial water management; Circular Economy.

INTRODUCTION

The phenomenon of global climate change, along with the escalating pressures from human activity, is placing considerable pressure on freshwater resources on a global scale. This has created a major concern with regard to water scarcity (Chin et al., 2022). Fluctuating precipitation patterns and rising demand, particularly in arid and semi-arid regions, have led to an unequal distribution of water supply, threatening both social development and industrial activities (Hashemi et al. 2024). This predicament calls for the formulation of water resources management tactics that are environmentally viable.

The industrial sector is one of the largest consumers of global freshwater, second only to agriculture (Lima et al., 2021). It is widely acknowledged that industries such as petrochemical refining (Hashemi et al., 2024; Mughees and Al-Ahmad, 2015), food processing (Lima et al., 2021), dairy (Espíndola et al., 2023), pulp and paper mills (Ahmetović et al., 2021; Vu et al., 2025) are recognized as "water-intensive" processes. For instance, the brewing process has been shown to consume between 4 and 8 liters of water for every one liter of product (Aremanda et al., 2022). The escalating costs of water supply and treatment, along with the increasing stringency (or stricter enforcement) of environmental discharge regulations, are forcing (or pushing) these industries to re-evaluate their water management strategies (Hashemi et al. 2024).

In response to these challenges, a transition from the traditional "take-make-dispose" model of industrial water management to one based on Circular Economy (CE) principles has become mandatory (Chin et al., 2022; Lima et al. 2021). In this new paradigm, wastewater is no longer viewed as "waste" but as a valuable "resource" to be recovered (Chin et al. 2022). The overarching objective of this approach is frequently termed Zero Liquid Discharge (ZLD), wherein the objective is to eliminate all liquid waste discharge from the facility by recycling all water within the process (Tong and Elimelech 2016). However, it is important to note that achieving ZLD or high recovery rates is not possible through arbitrary or isolated improvements (Manan et al., 2007). A systematic, holistic approach is required that views all of the plant's water flows as an integrated system. At this juncture, Water Pinch Analysis (WPA) emerges as one of the most powerful methodologies for industrial process integration (Hashemi et al., 2024; Lima et al., 2021).

This study provides a detailed review of the Water Pinch Analysis (WPA) methodology, drawing upon a comprehensive corpus of literature on the subject. In the second section of this study, entitled 'Methodology and Optimization', the author combines WPA's theoretical background, historical development, methodological calculation steps, network design rules, and the methodology's inherent limitations. This methodological analysis is integrated with economic optimization and a holistic 'nexus' (energy-water-carbon) analysis. The subsequent 'WPA Industrial Application Results' section provides a summary of the practical applications of the methodology and the concrete water savings achieved in various sectors, including petrochemical refineries, pulp and paper, food processing, and textiles. These savings are illustrated with case studies. Finally, the 'Conclusion' section emphasizes the importance of WPA as a holistic tool for industrial water management, while also discussing its limitations and future research directions.

METHODOLOGY

Pinch Analysis (PA), otherwise referred to as Pinch Technology, was first developed in the late 1970s and early 1980s by Bodo Linnhoff and his colleagues (Rani et al. 2024). This development largely emerged as a response to the sudden increase in fossil fuel prices in the late 1970s. The initial focus of this methodology was on Heat Integration, with the objective of maximizing heat transfer between processes and minimizing external energy (utility) consumption (Rani et al., 2024). The evolution of the methodology occurred in the mid-1990s with the pioneering work of Wang and Smith (1994). This adaptation came roughly 20 years later compared to the energy case and was driven by new government legislation aimed at improving the environmental impact of industrial operations. The direct analogy between heat transfer (enthalpy) and mass transfer (concentration) was recognized, and the fundamental principles of Pinch Analysis were adapted to wastewater minimization (Wang and Smith 1994). This development signified the genesis of the methodology that would subsequently be recognized as Water Pinch Analysis (WPA). Since its inception, WPA has evolved from a rudimentary graphical tool into a comprehensive methodology that incorporates water regeneration (treatment), operational constraints, financial analyses, and ZLD targets. WPA is regarded as one of the two primary systematic optimization methods alongside Mathematical Programming (MP) (Ahmetović et al. 2021; Najafi et al. 2024), yet although MP (often formulated as a Mixed-Integer Non-Linear Programming - MINLP problem) is powerful, it is distinguished by its capacity to provide robust "physical insight" into the process constraints (Ahmetović et al. 2020; Shukla and Chaturvedi 2021).

The fundamental objective of WPA is realized in main two distinct phases: The initial step is to determine the minimum freshwater requirement, which is referred to as targeting. The subsequent step is to achieve these targets through network design. However, it is possible to say that WPA analysis can be carried out with the stages given in Figure 1.

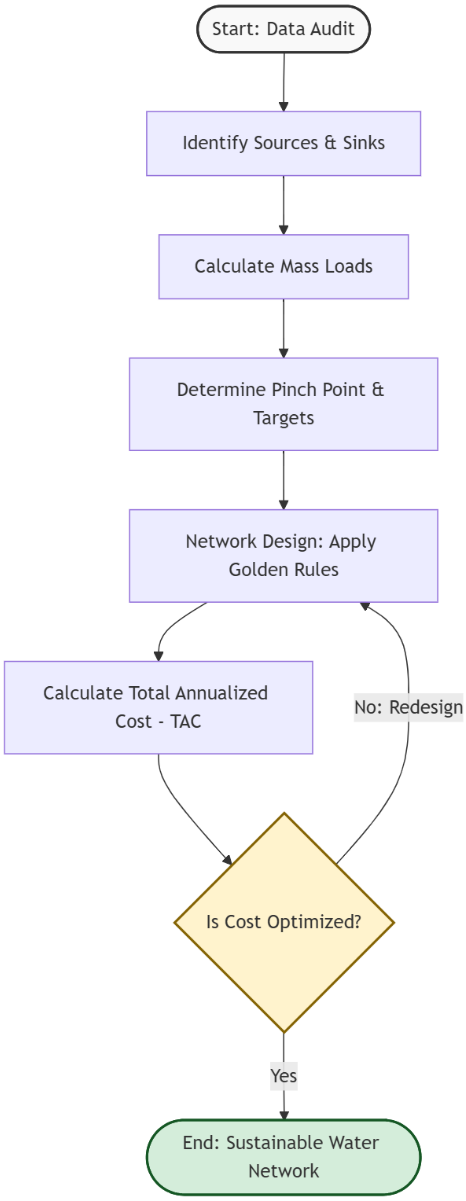

Figure 1. A simplified flowchart of the Water Pinch Analysis (WPA) methodology.

The WPA methodology commences with the identification of water flows and constraints within the

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process. As Espíndola et al. (2023) demonstrate, a comprehensive listing has been compiled of all water-using operations (water "sinks") and wastewater-generating operations (water "sources") within the facility. This data collection step is a critical and often difficult phase, particularly in retrofit projects, as older industrial complexes may lack the minimal instrumentation (e.g., flow meters) required for reliable data collection. The entire analysis is based on one or more selected indicator pollutants (Espíndola et al. 2023; Lima et al. 2021). The selection of contaminant is contingent upon the nature of the process; for instance, Total Dissolved Solids (TDS), Electrical Conductivity (EC) and Chemical Oxygen Demand (COD) are prevalent in petrochemical refineries, food and dairy industries (Hashemi et al., 2024; Mughees, & Al-Ahmad 2015; Mohammadnejad et al., 2012; Espíndola et al., 2023; Lima et al., 2021), while COD, Adsorbable Organic Halogens (AOX), or Colloidal Substances (CS) are employed in the pulp and paper industry (Shukla et al., 2013). This indicator pollutant selection reveals one of WPA's most significant methodological limitations, namely the tendency of classical WPA to focus on a single-contaminant assumption for simplicity (Chin et al. 2022). This is a significant drawback, as the WPA methodology struggles to be applied effectively to multi-contaminant systems. However, the composition of industrial wastewater renders it complex, and it is often characterised by the presence of multiple contaminants.

In many industries, such as the PPI, the critical factor limiting water recycling (closing the mill) is the buildup of multiple Non-Process Elements (NPEs) like calcium, magnesium, or manganese, which accumulate and cause severe operational problems such as scaling, corrosion, and deposit formation. In a study by Esmaeeli and Sarrafzadeh (2023), the use of COD, TDS, and TSS separately as indicators for the same paper mill wastewater yielded inconsistent and different minimum water targets (4.0%, 18.9%, and 36.9%, respectively). This demonstrates that WPA must be applied with great care in multiple-contaminant systems; otherwise, the targets may be incorrectly identified. This limitation is a primary reason why Mathematical Programming (MP) is often used as a complementary or alternative approach, as its superstructures can be designed to handle multiple constraints simultaneously.

For the WPA analysis, the following data must be collected for each operation: the required water flow rate (F_i) and the maximum allowable contaminant concentration (C_sink,i_max) for each sink i; and the available flow rate (F_j) and the current contaminant concentration (C_source,j_in) for each source j (Hashemi et al. 2024; Espíndola et al. 2023). The freshwater source concentration should be assumed to be zero. Table 1 provides an example of how this baseline data is listed for two contaminants in a petroleum refinery case study.

Table 1. An example the water source characteristics for WPA calculations (Adapted from Hashemi et al. 2024)

Operations		**Flowrate (m^3/h)**	**CFP_in, max (ppm)**	**CFP_out (ppm)**	**CSP_in, max (ppm)**	**CSP_out (ppm)**
OP1 (Desalter)	Sink	6	3	-	400	-
	Source	6	-	8	-	1000
OP2 (Firefighting)	Sink	10	3	-	450	-
	Source	10	-	6	-	870
OP3 (Cooling Tower)	Sink	65	5	-	750	-
	Source	65	-	13	-	1350

In the implementation of the water pinch technique, while multiple targeting tools exist, a graphical method based on the concentration composition curve can used to determine the pinch point. These methods include graphical tools like Limiting Composite Curves and Material Recovery Pinch Diagrams, as well as algebraic tools like the Mass Problem Table or Water Cascade Analysis (WCA).

The data collected and the calculation method (e.g., focusing on mass load Δm vs. flow rate F) depend on the chosen WPA approach. The two main approaches are the 'Fixed Load' problem, where water is treated as a mass separating agent (e.g., in applications like vessel cleaning, solvent extraction, or gas absorption) to remove a specific contaminant load, and the Fixed Flow Rate problem, which focuses on water sources and sinks where flow rate itself is the primary constraint and where inlet/outlet flow rates may not be uniform.

Key parameters for this methodology encompass the minimum water requirement, transferred mass load, inlet and outlet concentrations of the index pollutant, and water losses for each operational unit (Table 2).

Theoretically, this data collection is a critical first step, but practically, it presents a significant challenge in existing industrial (retrofit) projects, which often suffer from a "lack of information" and "minimal instrumentation" (such as flow measurements) or complex Non-Process Element (NPE) buildups. The transferred mass load (Δmopi) for an operational unit 'i' is calculated using first equation given in below. The other calculation equations used in this study are shown in below (Hashemi et al. 2024)

$$\Delta mopi=1000(Cout-Cin)\times Fopi$$

$$Fmin=(Cout-Cin)\times 1000\Delta mopi$$

$$F=Floss\times Cpinch(Cpinch-Cin)$$

$$Ctotout=\sum Fopi\_min(Fop1\_min\times Cop1\_out)+(Fop2\_min\times Cop2\_out)+\ldots$$

Table 2. The concentration and the transfer mass load for single pollutant (COD) (Adapted from Hashemi et al. 2024)

Operations	**Qin (m^3/h)**	**Qout (m^3/h)**	**CFPin (ppm)**	**CFPout (ppm)**	**Mass Load (kg/h)**	**Total Mass Load (kg/h)**	**Fopi_min (m^3/h)**
OP1 (Desalter)	6	6	3	8	0.01	0.01	2
OP2 (Firefighting)	10	10	3	6	0.03	0.04	10
OP3 (Cooling)	65	65	5	13	0.52	0.56	65
							Total = 77
f_opi: Operational water flow rate; f_min: Theoretical minimum water flow rate based on mass load and concentration limits.							

The variables in the equations have the following meanings: $\Delta mopi$ is the mass load for an operational unit 'i' (kg/h), Cout and Cin are the outlet and inlet concentration, respectively (ppm), fopi is the freshwater flow rate for unit 'i' (m^3/h), floss is the water loss for unit 'i' (m^3/h), Cpinch is the pollutant concentration at the pinch point (ppm), and Fmin is the minimum required water consumption (m^3/h).

In the double pollutant approach, when one of the pollutants is known in a concentration interval, the following equation was used to determine the secondary pollutant in the same interval (Hashemi et al. 2024):

$$(CFPout-CFPin)(CFP,X-CFPin)=(CSPout-CSPin)(CSP,X-CSPin)$$

In this equation, CFPout and CFPin, and similarly CSPout and CSPin, are related to the inlet and outlet concentrations of first pollutant (FP) and second pollutant (SP) from the predetermined operations. C_FP,X and C_SP,X represent the intermediate pollutant concentrations at a specific interval point X. For instance, in an operational unit divided into multiple intervals where only the inlet and outlet concentrations are known, this equation is utilized to calculate the unknown concentration for the intermediate interval..

These equations provide the inputs for the targeting methods. The minimum water requirement is determined using the composite curves method. While graphical composite curves (plotting concentration vs. mass load or mass load vs. flow rate) are common, algebraic methods like the mass problem table or Water Cascade Analysis (WCA) are also other targeting tools. In this graphical method, pollutant concentration is plotted against mass load. Effluents with concentrations below the Pinch Point are prioritized for reuse in units capable of accepting lower-quality water. Figure 2 illustrates this analysis for CFP and CSP, identifying Pinch Points at 6 ppm and 400 ppm, respectively. This graphical targeting method and the identification of the Pinch Point (C_pinch) as an example.

Once the targets are set, the Network Design phase begins, which establishes the piping network to achieve these targets. The Pinch Point divides the problem into two independent sub-problems: Below the Pinch (the low-concentration, mass-deficit region) and Above the Pinch (the high-concentration, mass-surplus region). To achieve the minimum target, three 'Golden Rules' must be followed: (1) Freshwater must not be used to satisfy demands above the Pinch; (2) Wastewater below the Pinch must not be sent directly to discharge; (3) Water must not be transferred across the Pinch (from above to below). During the design phase, matching is performed by adhering to these rules, often using systematic methods like the Nearest Neighbor Algorithm (NNA). NNA is a heuristic algorithm that aims to match an available water source (wastewater stream) with a water demand (sink) that is 'nearest' in terms of pollutant concentration. A Sample water recovery route (network) design and flow chart for single pollutant WPA are given in Figure 3.

The theoretical network design derived from Water Pinch Analysis (WPA) is not the end of the engineering process, but merely a starting point. The fundamental limitation of the WPA methodology is that it inherently targets minimum resource consumption, namely Operating Expenditure (OPEX). This focus is a core concept of the methodology, which aims to maximize process recovery (i.e., the overlap of composite curves) while simultaneously considering the related equipment investment. However, this focus does not guarantee the lowest Total Annualized Cost (TAC), as a design that achieves the theoretical minimum water target might require highly complex piping networks or expensive regeneration (treatment) units. This, in turn, can excessively increase the Capital Expenditure (CAPEX).

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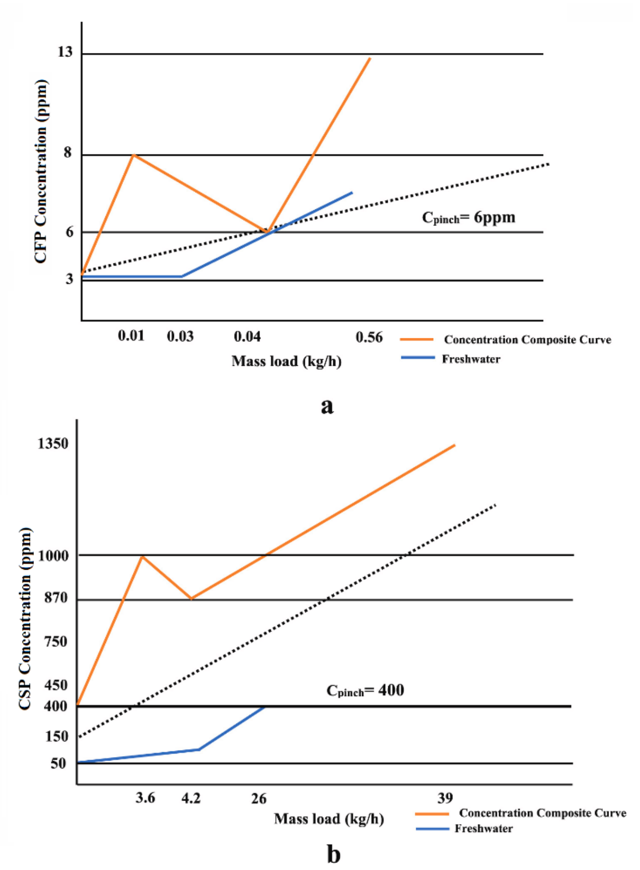

Figure 2. Identification of concentration composite curves and the Pinch Point (Adapted from Hashemi et al. 2024)

This economic trade-off represents a significant barrier; the adoption of WPA has lagged behind its energy equivalent precisely because savings derived solely from freshwater and wastewater reductions are often insufficient to warrant the combined costs of detailed analysis and capital investment. Therefore, a successful design must be optimized to balance this trade-off between OPEX and CAPEX. OPEX represents the sum of all annual costs required to keep the system operational, with its main components being freshwater intake (F_FW), wastewater discharge (F_WW), and the energy (E_Total) for pumping or treatment, as expressed in the formula:

$$\text{OPEX} = (\text{F\_FW} * \text{c\_FW}) + (\text{F\_WW} * \text{c\_WW}) + (\text{E\_Total} * \text{c\_Elec}) + \text{C\_Other}$$

CAPEX, on the other hand, is the total initial investment cost for new equipment. To estimate this, the Total Purchased Equipment Cost is often used as a base, which is calculated using capacity-based correlations given in below or via detailed equipment cost calculations:

$$\text{Equipment Cost (\$)} = a + b * (\text{Capacity})^c$$

This base cost is then converted into the total project cost (Total CAPEX) using a multiplier such as the Lang Factor (F_Lang), a coefficient based on the plant type, as in:

$$\text{Total CAPEX} = (\text{Total Equipment Cost}) * \text{F\_Lang}$$

To optimize the design, the one-time CAPEX investment must be made comparable to the recurring OPEX. This is achieved by annualizing the capital cost through an Annuity Factor (AF), which is determined by the annual interest rate (i) and the project's economic life (n):

$$\text{AF} = [i * (1+i)^n] / [(1+i)^n - 1]$$

$$\text{Annualized CAPEX} = \text{CAPEX} * \text{AF}$$

The ultimate goal of the optimization is to find the design with the lowest Total Annualized Cost (TAC) defined as:

$$\text{TAC} = (\text{Annual OPEX}) + (\text{Annualized CAPEX})$$

WPA Industrial Application Results and Freshwater Savings

Water Pinch Analysis (WPA) is a proven engineering tool that has provided concrete, measurable benefits in various industries worldwide. Case studies from the provided literature demonstrate the methodology's direct impact on reducing freshwater consumption and optimizing wastewater management. The effectiveness of WPA in water-intensive sectors like petrochemicals and refining is particularly striking. For example, in one petroleum refinery, WPA application reduced freshwater consumption by 45% with a single-contaminant approach and by 56% with a double-contaminant (TDS and COD) approach (Hashemi et al. 2024). In another petrochemical plant, a 43.8% reduction in freshwater savings was achieved for single contaminant (COD) (Mughees and Al-Ahmad 2015). In ethylene production, WPA focusing on cooling water (CW) circuits identified potential water and energy consumption reductions of 32% and 98% in the steam turbine condenser (Najafi et al. 2024).

The methodology has shown similar success in the pulp and paper industry. Reviews combining WPA and Mathematical Optimization (MO) methods in this sector have identified a wide potential for water savings, ranging from 20% to 80% (Ahmetović et al. 2020; Baghel et al. 2019). In specific case study, a 75.4% freshwater consumption reduction target in a straw pulp paper mill have been reported (Li et al. 2016).

The food and beverage industry has also benefited significantly from WPA. In a dairy plant case study, WPA scenarios involving regeneration with membrane technologies (MBR+NF) demonstrated the potential to reduce freshwater use in the overall process by up to 95.4% (Espíndola et al. 2023). In a potato-processing food plant, WPA was used to achieve a 55% reduction in raw water consumption and a 45% reduction in discharged wastewater volume (Lima et al. 2021). In a sugar refinery, WPA targeted 100% water recovery for process water (zero freshwater intake) (Balla Ali et al. 2018).

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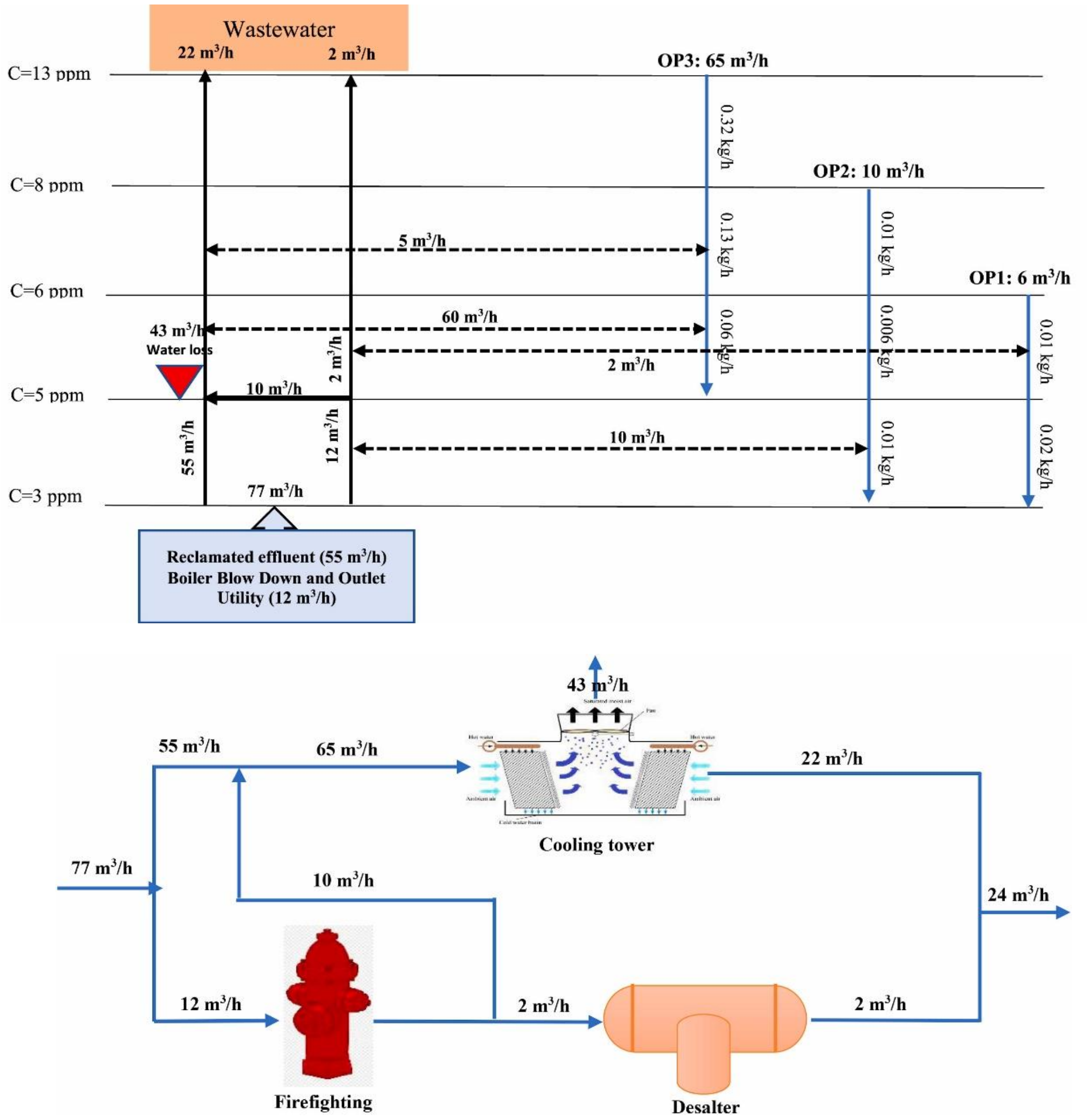

Figure 3. A Sample water recovery route (network) design and flow chart for single pollutant WPA (Adapted from Hashemi et al. 2024).

The flexibility of the methodology has been demonstrated in other industrial applications. In the high-polluting textile industry, a WPA case study identified a freshwater saving potential of 36.14% and a wastewater reduction target of 56.4% (Miskah et al. 2023). In a PET recycling plant, WPA application achieved 47.7% in freshwater savings. Furthermore, significant water-saving potentials have been identified using WPA in diverse sectors such as brick manufacturing (Skouteris et al. 2018) and lead-acid battery recycling (López Zavala et al. 2024). These results show that WPA not only significantly reduces freshwater use (and associated OPEX) but also alleviates the load on wastewater treatment plants, thereby directly reducing environmental impacts.

From a wider perspective, while these case studies demonstrate significant theoretical savings ranging from 20% to over 90%, the industrial realization of these targets faces complex challenges. The primary constraint is often economic rather than technical; as indicated in the methodology, achieving the final incremental water saving often requires disproportionately high capital investment (CAPEX) in regeneration units, which may not offer a favorable payback period compared to current freshwater costs.

CONCLUSION

In an era where climate change and water scarcity exert increasing pressure on industrial sustainability, Water Pinch Analysis (WPA) stands out as an indispensable methodology. This study has shown that WPA is not merely a theoretical optimization tool, but a systematic roadmap, rooted in mass balance principles, for analyzing complex industrial water networks. Its practical application and efficacy have been proven across the most water-intensive industries, from petrochemical refining to food processing and paper production.

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The "Targeting" and "Network Design" capabilities of WPA provide engineers with a clear pathway to achieving minimum freshwater consumption. Real-world case studies have verified that this approach can yield freshwater savings and plays a critical role in achieving Zero Liquid Discharge (ZLD) goals.

However, as emphasized in this study, the success of the methodology cannot be measured by theoretical water minimization targets alone. Classical WPA applications face significant limitations, such as the single-contaminant assumption, the presumption of steady-state operation, and the disregard for physical plant layout constraints. Most critically, the fact that a minimum water target (OPEX) does not always guarantee the minimum Total Annualized Cost (TAC) is the greatest barrier to the financial feasibility of these designs.

Future work must focus on strengthening the bridge between the theoretical targets identified by WPA and the realistic financial optimization (CAPEX/OPEX balance) required to achieve them. Furthermore, holistic Energy-Water-Carbon 'Nexus' analyses, which examine the trade-offs between water minimization and its impact on energy consumption and carbon emissions, are crucial for evolving WPA into a more powerful sustainability tool. In conclusion, Water Pinch Analysis is a cornerstone of industrial water management, playing a central, proven, and economically vital role in the implementation of resource efficiency and Circular Economy principles.

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Conflict of Interest

The author declares no conflict of interest.

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