

Multi-Pollutants Water Cascade Analysis for Industrial Water Minimization

Teba K. Husen, Mohammad N. Faris, Mohammad A. Taher

*Department of Chemical Engineering, Faculty of Engineering, Basra University, Iraq;
teba.kadhim@uobasra.edu.iq, mahmod.faris@uobasrah.edu.iq
Department of Chemical and Petroleum Refining Engineering, Basrah University for Oil and Gas, Iraq;
moh.may@buog.edu.iq*

This research article studies building a Water Cascade Analysis (WCA) method that can rationalize multiple industrial environments that involve multiple pollutants. The method uses an integrated numerical targeting step and network redistribution to minimize freshwater usage as well as wastewater discharge. The method was, thus, applied using the case study by Hashemi et al. (2024) [1], where the analysis first identified a total of three units that accounted for most water consumption: these were the Desalter unit, the cooling tower, and the firewater system. Both Chemical Oxygen Demand (COD) and Total Dissolved Solids (TDS) were adopted as the two main contaminants. The results of the single-contaminant analysis showed that the minimum freshwater requirement was 44.62 m³/h when considering COD, while it decreased to 34.68 m³/h when considering TDS. This reduction amounts to between 19% and 25% of the refinery's total consumption (175 m³/h). The volume of wastewater produced was, therefore, identical to these figures, reflecting the accomplishment of the Pinch Point as evidenced by the cascade tables for each pollutant individually. Next, the sequential contaminant analysis (A→B) and (B→A) was performed. The results of the first scenario showed consumption rising to 44.87 m³/h owing to the need to dilute the concentrations of the second contaminant. On the other hand, the best performance was achieved in the second scenario (B→A) with freshwater requirements as low as 44.83 m³/h. As a result, TDS was identified as the Limiting Pollutant. A comparison between the methodology developed and the Water Pollutant Analysis (WPA) method employed in the reference study revealed that the use of freshwater was lowered from 99 m³/h to less than 45 m³/h in the proposed method, whereas wastewater discharge was reduced from 52 m³/h to about 44.8 m³/h. The findings verify that the proposed methodology serves as a simplified, efficient, and numerical means of water reuse network design in multi-contaminant industrial systems. Besides achieving considerable water savings, it also lessens the environmental impact, thus presenting itself as a suitable instrument for use in oil refineries and industrial facilities with complex water systems.

Keywords: Water Pinch Analysis; Multi-Pollutants Water Cascade Analysis; Freshwater Targeting; Wastewater Minimization; Process Optimization; Industrial Water Network.

Abbreviations Used: AI – WCA – Water Cascade Analysis; COD – Chemical Oxygen Demand; TDS – Total Dissolved Solids; WPA – Water Pollutant Analysis; m³/h – Cubic meters per hour

Corresponding Author: Teba K. Husen; Department of Chemical Engineering, Faculty of Engineering, Basra University, Iraq. E-mail: teba.kadhim@uobasra.edu.iq

INTRODUCTION

Integrating water is one of the vital parts of process engineering in the industrial facilities that are heavily affected by rising water demand and environment-related constraints, needing less freshwater consumption and wastewater discharge. The gradual change of this area can be traced to the seminal work of Wang and Smith (1994) [2]. They set up the scientific foundation for Water Pinch Analysis by using composite curves to identify the area with the least freshwater requirement. Their initial study was very efficient in reducing water usage by over 25%. Kuo and Smith (1998) [3] furthered this domain significantly by proposing a Pinch principle-based algorithm for designing industrial water networks. By this means, in their several oil refineries, they discovered the

water consumption reduction potentials beyond 15 to 30 percent. Hallale (2002) [4], just before the new millennium, introduced the Water Surplus Diagram method to the field as a graphical alternative to the Pinch method. It turned out to be extremely effective in locations with complex flow patterns, leading to savings in fresh water of up to 34% over the traditional methods. A milestone in the field's change was when El-Halwagi (2003) [5] came up with a single system for sustainable engineering via Process Integration for Pollution Prevention (PIPP). The method linked the water integration techniques with thermal integration and stated that by integrating different resources, the savings could be more than 40% of the total water and energy consumption.

In 2004, the three Manan, Tan, and Foo (2004) [6] made a different qualitative change by inventing Water Cascade Analysis (WCA), a direct numerical method for finding minimum freshwater needs without any graphical analysis. It was quickly adopted in pulp mills and oil refineries where the reductions ranged from 20 to 52%.

Bagajewicz (2000) [7] was another major contributor with his all-inclusive mathematical model for water network design, proving that algorithmic optimization could bring water demand down by half in petrochemical industries. Along similar lines, Kim et al. (2008) [8] leveraged water pinch technology to create and fine-tune a water reusing network for an eco-industrial park, coming up with three reuse scenarios that interconnect various industrial units. Their optimized network resulted in the total freshwater consumption going down by over 30% and water-related costs by close to 20%, thus enabling a pinch-based design to be highly effective for inter-plant water reuse.

Using the WCA method, Manan et al. (2007) [9] successfully reduced water consumption by 31% in a paper mill through internal flow redistribution. Later, Foo (2007)[10] took the method further to cover situations involving impure fresh water, insinuating that the introduction of partially treated streams could cause the Pinch point to move and water consumption to drop by 10–18% more.

As multi-contaminant systems became a necessity, Mohammadnejad et al. (2010)[11] came up with a novel Water Pinch-based algorithm for lowering water consumption in an oil refinery, which eventually led to 22% less freshwater use and 19% less wastewater discharge. Moreover, Fan et al. (2012)[12] devised a design process for multi-contaminant water networks by merging Pinch Optimization with mathematical programming techniques. Their research resulted in water consumption being cut down by as much as 45% compared to the traditional methods.

In textiles, the research conducted by Shabbir et al. (2022) [13] analyzed the effectiveness of multi-contaminant Water Pinch Analysis and concluded that the method could save 28% of water while lowering the contaminant concentrations to below the regulatory limits. The paper by Abdullahi (2016)[14] in oil refineries indicated that using Water Pinch resulted in a 33% decrease in water demand, and it was also possible to recover 18% of the wastewater without extra treatment. At the level of fully-fledged industrial sites, Ahmad Fadzil et al. (2020)[15] came up with the TSC-WCT idea, showing that site-wide integration is capable of producing savings between 40 and 60% of freshwater when centralized reuse systems are available.

Yoo et al. (2007)[16] also presented an extensive review of the progression of water integration technologies and put great emphasis on the fact that a combination of WCA, WPA, and mathematical optimization is crucial in achieving sustainable design solutions. They also reported that most industrial applications can lead to water savings from 20 up to 50%. The study by Chen (2008)[17] was instrumental in transforming water integration concepts to batch plants where water can be reused between batches thus total water demand can be cut by 27%. Similarly, Adekola (2011)[18] demonstrated that multipurpose plants could achieve water savings up to 30% through Water Source Diagram, which is a tabular version of Cascade analysis methodology. Lastly, Wan Alwi (2023)[19] offered an extensive review of water and energy integration and identified that the present trends are geared towards hybrid models that are capable of dealing with multiple contaminants and complex environmental and economic criteria simultaneously.

After such scientific progress, it seems that the only remaining problem is the scarcity of tools that can handle complex multi-contaminant water networks without complicating the application too much. Therefore, there is a pressing need in the industry for the development and deployment of Multi-Pollutant Water Cascade Analysis methods as an essential step towards more efficient and eco-friendly industrial water management.

There has been a series of dramatic qualitative changes in the way industrial water network integration methods have been treated. The transformation can be traced back to the exhaustive review by Jeżowski (2010) [20], which not only presented an overview of water network design methods but also divided them into two groups: optimization-based mathematical methods and heuristic methods of the Pinch and Cascade type. Additionally, the author highlighted the research gap with respect to multi-contaminant networks and internal water regeneration. Along the same lines, Gouws and Majozi (2010) [21] provided an insightful review of water-saving methods in batch processes with a focus on time-based models and the integration of scheduling with network design. They showed that the right handling of the temporal dimension results in dramatically lower water consumption in batch plants than in static ones.

On the structures side of the networks, Cao et al. (2004)[22] proposed a design for water networks with 'internal mains' for several contaminants. This allowed the network to be a single more accurate model of reuse and recycling routes instead of having different designs for each contaminant. They proved through a few examples that the structure leads to less fresh water needs than the traditional ones. The work of Su et al. (2012)[23], who suggested a new design method for multi-contaminant water networks with a single internal main, using a direct numerical formulation to determine flow paths, was the next step in this development.

This made it possible to do the two tasks of reducing freshwater consumption and wastewater generation simultaneously with relative computational simplicity. To enhance the adaptability of multi-contaminant networks, Zhao et al. (2014) [24] created a method for designing water networks with two internal water mains, thus enabling the separation of flowing different contaminant characteristics into two paths in the same network. They illustrated through industrial cases that this framework offers more reuse possibilities and lessens the load of the treatment units.

Within a broader framework, Fan et al. (2012)[25] proposed the notion of "Concentration Potential" for the design of multi-contaminant networks. They separated the units into those having fixed flow rates and processes with fixed contaminant loads, thus obtaining a systematic design method which makes it possible to use the concept for targeting water networks that save freshwater in complicated systems. Inspired by the idea of internal regeneration, Li et al. (2015)[26] described an examination of multi-contaminant water networks with regeneration recycling.

They incorporated treatment units in the model and studied the effect of removal efficiency on water consumption and total cost, thus showing the significance of the precise selection of regeneration unit locations for the simultaneous lowering of freshwater and wastewater. Poplewski (2011)[27], from a different angle, has resolved the design uncertainty issue by water network design model using stochastic optimization, thus showing that consideration of contaminant loads and concentrations fluctuations in the design model results in more operationally reliable solutions while the freshwater consumption remains low.

In the area of batch processes, Lee et al. (2014)[28] modelled the design of minimum water networks in plants with fixed schedules and variable

production rates, thereby going one step further to the works of Majozi. They combined the time scheduling model with the water network structure and demonstrated that connecting these two decisions leads to a more efficient use of internal water sources. Correspondingly, Li and Majozi (2017)[29] suggested a method of designing batch water networks within a flexible scheduling framework.

They relied on a ranking matrix for connections between sources and sinks in order to find the best reuse matches, and through case studies, showed that the integration of temporal flexibility and network design greatly increases the potential for reuse.

Likewise, Bazolana and Majozi (2017)[30] worked on the water network design for a multi-purpose batch plant with a central regeneration unit by electrodialysis. They coupled the scheduling model with the regeneration unit design model, thus demonstrating that the selection of regeneration unit size and working conditions significantly influences the trade-off between freshwater consumption and energy.

At a more detailed level in regards to treatment units, Yang, Salcedo-Díaz, and Grossmann (2014)[31] demonstrated a comprehensive model for optimizing water networks with real regeneration units. They employed numerous "short-cut" models for treatment (sedimentation, filtration, ion exchange, reverse osmosis, biological treatment), incorporated investment and operating costs as well as uncertainty in contaminant loads and applied the model to industries such as oil refining and metal finishing to showcase the potential of multi-contaminant networks.

Optimization of Water Network Integrated with Process Models (2012)[32] also involved the issue of coupling detailed process unit models with water network design. It shows that depending on simplified single-path models can result in a wrong estimation of the minimum fresh water requirement, and that coupling process modeling with network synthesis provides more realistic and feasible solutions.

Thinking beyond a single plant, Ramin et al. (2019)[33] came up with a model for the design of water reuse networks in the scope of industrial symbiosis, where water is considered a shared resource among several facilities within an industrial park. An optimization model was created to reduce the use of freshwater and emissions at the level of the whole site, not just at the level of an individual plant.

Nezungai et al. (2016)[34] focused on the optimization and design of water networks by means of a superstructure framework within the classical intra-plant models. The issue of lowering freshwater and wastewater was put forward as a MINLP problem in this paper, and the research demonstrated that by extending the superstructure to also include recycling and regeneration options, a more efficient solution could be achieved than that of traditional, limited designs.

In the same way, Jakata et al. (2022) [35] presented a novel design framework for membrane-based (nanofiltration) regeneration networks for multi-contaminant water aimed at determining the network of regeneration units within the industrial water system by means of a superstructure and optimization algorithms. Their main emphasis was on choosing the arrangement of membrane units and balancing energy and water costs. The study "System Analysis and Optimization of Multi-Contaminant Water Reuse Network with and without Regeneration"[36] carried the idea further at the algorithmic level.

It put forward an analytical model for multi-contaminant water reuse networks with and without regeneration units, combined with a hybrid

algorithm based on a Genetic Algorithm to explore different network configurations. The study made it clear that the careful way of adding regeneration units could lower not only water consumption but also the total cost of the water network. The gradual transition made through all these studies from simple single-contaminant models to sophisticated multi-contaminant models that also include features like realistic regeneration units, temporal scheduling, uncertainty, and the industrial site level is very obvious.

It thus quite reasonably opens the door for the development and implementation of methodologies such as Multi-Pollutant Water Cascade Analysis, which seeks to achieve a compromise between heuristic simplicity and the capability of dealing with complex, multi-contaminant networks.

METHODOLOGY

This study applies Water Cascade Analysis (WCA) to determine freshwater and wastewater targets in industrial systems that handle multiple pollutants. Conventional WCA, developed by Manan et al. (2004) for a single contaminant, is extended here to account for the simultaneous presence of pollutants such as chemical oxygen demand (COD), total dissolved solids (TDS), ammonia, and heavy metals. The proposed methodology identifies the minimum freshwater demand and wastewater discharge under multiple quality constraints. Water recycling and reuse are used in the design and targeting process of the water network. A single contamination is considered first in the demonstration of the method, then the multiple contamination problem is used to demonstrate the extended method and steps of the water network design are explained.

System Description and Mathematical Framework

The water cascade analysis considers a water network composed of process units (sinks) that require water with specified quality constraints, and process effluents (sources) that contain varying concentrations of pollutants.

Sources: water streams leaving process units, cooling blowdown, condensates, and wastewater streams with known pollutant concentrations.

Sinks: water demands for washing, cooling, or dilution, each with maximum allowable concentration limits.

Pollutants: indexed as $i = 1, 2, \dots, n$ (e.g., COD, TDS, NH_4^+).

For contaminant i , the load balance is given as:

$$L_i = F \times C_i \quad \dots (1) [20]$$

where L_i is the contaminant load (kg/h), F is the volumetric flowrate (m^3/h), and C_i is the contaminant concentration (mg/L).

Each sink j must satisfy:

$$C_{i,in,j} \leq C_{i,max,j} \quad \forall i \quad \dots (2)[20]$$

$$F_{ski} = F_{fw} + F_{SRI} \quad \dots (3)[37]$$

$$F_{ski} * C_{ski} = F_{fw} * C_{FW} + F_{SRI} * C_{SRI} \quad \dots (4)[37]$$

Where:

F_{ski}, C_{ski} the flow rate and concentration of contaminant i in the sink.

$F_{fw} * C_{FW}$ the flow rate and the concentration of the fresh feed.

F_{SRI}, C_{SRI} the flow rate and the concentration of contaminant i in the source.

The freshwater requirement for contaminant i is obtained by applying the cascade procedure separately.

Analysis, targeting and design for a single contaminant

For a single contaminant problem, the Water Cascade Analysis (WCA) developed by Manan et al. (2004) is used to determine the minimum freshwater target for a process based on the possibility of using the available water sources. A table is constructed to determine the net water source and water demand at each purity level. The construction of the Water Cascade Table will be demonstrated using the case study from Hashemi et al. (2024). Three processes were selected with high water consumption, the desalter unit, the cooling tower and the firefighting unit. Chemical oxygen demand (COD) and total dissolved solids (TDS) were selected as indicator pollutants, where each pollutant is considered independently.

Cascade construction for a single pollutant

Unlike graphical techniques of the water pinch analysis, Water cascade analysis provides a numerical framework that simplifies the targeting of water reuse and recovery opportunities in industrial systems. The cascade table is designed to identify the minimum freshwater objective for a process based on the possibility of using the given water sources. Table 1 shows the generic cascade table representation for a single contaminant.

The construction of Table 1 is described below:

- 1- Column 1 lists, in ascending order, the pollutant concentration amounts of the streams (from the lowest concentration (the cleanest) to the highest concentration (the dirtiest)).
- 2- Column 2 computes the variations in concentration between two successive levels, $(C_{n+1} - C_n)$.
- 3- Columns 3 and 4 show the sources' and sinks' total flow rates at every concentration level, (ΣF_{SRI}) and (ΣF_{SKI}) .
- 4- Column 5 shows the variations in sink and source flow rates, $(\Sigma F_{SRI} - \Sigma F_{SKI})$.
- 5- Column 6 computes the cumulative value of flow rate variations.
- 6- Column 7 calculates the pollutant loads at every level, $(\Delta load = F_{cum,n} * \Delta C_n)$
- 7- Column 8 computes the cumulative load.
- 8- Column 9 figures the freshwater needed at every level, $(Cumfresh_n = \frac{cumload_n}{cn-cfw})$.

Table 1: Generic cascade table representation for a single contaminant [38].

2.3. Analysis, targeting and design for multiple contaminants

One of the major challenges that industrial systems have to deal with is the presence of multiple contaminants. Each pollutant has a different effect on the industrial processes, e.g. some operations might require water of high purity while others can tolerate water with a

certain degree of contamination. Due to this, the distribution of reused water among the various processes becomes complicated. Additionally, the identification of the "pinch point", which is the minimal amount of fresh water needed, gets complicated as well when there are multiple interacting pollutants instead of a single one.

In order to resolve this issue, the waterfall table approach is modified by looking at each pollutant separately. A unique water cascade table is made for every pollutant. For example, in the case where pollutants A and B are present, the first step is to make a cascade table for pollutant A which is treated as if it were the only contaminant. After that, a design phase follows where the proper sources are assigned to each sink. The next step is to test the appropriateness of these allocations against pollutant B. This means checking whether the concentration of pollutant B in each sink is in agreement with that in the corresponding source. An allocation is considered valid if the pollutant load in the source is equal to or less than that in the sink. If not, more fresh water has to be added to lower the concentration. The results of this method revealed that the best source allocation for a sink is the one that fulfills the pollutant load limitations to the greatest extent possible.

Starting with pollutant B and checking its compatibility with pollutant A, the process is repeated. Eventually, the best scenario, which is the least use of fresh water and the smallest volume of wastewater, is chosen. Afterwards, a water reuse network is planned based on this best scenario, ensuring that each process receives water of the right quality while considering all contaminants.

However, this method is outweighed by its advantages in terms of waste reduction, decreased operational costs, and environmental protection. Reusing every drop of water effectively is a move toward a more sustainable and efficient industrial future.

The key steps for designing a multi-pollutant water reuse network can be summarized using the modified water cascade table as follows:

The primary objective of this design is to reduce reliance on freshwater and minimize the production of wastewater. To achieve this, the following steps are followed:

Industrial Process Analysis:

This step involves studying industrial operations to identify:

- **Sources:** processes that consume large volumes of water
- **Sinks:** processes that generate significant amounts of wastewater

In addition, the flow rate for each source and sink must be determined. This analysis helps prioritize design efforts by focusing on the most impactful processes.

Identifying Key Pollutants:

Since pollutants have a significant impact on water quality, it is essential to analyze the water to determine their types and concentrations.

A Water Cascade Table for the First Pollutant Is Constructed :

- The first pollutant is treated as if it were the sole contaminant present in the system.
- This assumption allows the initial design to focus exclusively on its concentration constraints.

Water Distribution for the First Pollutant Is Designed:

Based on the constructed cascade table, water sources are allocated to sinks in manner that ensures the concentration of the first pollutant remains within acceptable limits.

Compatibility with Other Pollutants Is Tested :

- Once the distribution for the first pollutant has been designed, its validity is assessed in the context of all other pollutants.
- The pollutant loads in each sink are examined to determine whether they comply with the permissible thresholds for every contaminant.
- If any pollutant is found to exceed its allowable limit, the distribution is adjusted—typically through the addition of freshwater to dilute concentrations and restore compliance.

The process is repeated for each pollutant:

- The steps beginning from the construction of the water cascade table (Step 3) are repeated individually for each pollutant.
- Each pollutant is treated as if it were the only one present in the system to ensure accurate initial allocation before compatibility testing.

The optimal scenario is selected:

- The scenario that results in the lowest freshwater consumption and the least wastewater generation is selected.
- This scenario is adopted as the foundation for designing the final reuse network.

As shown in Figure 1, the flowchart outlines the sequential and iterative steps involved in designing a water reuse network that accounts for multiple pollutants. Figure 1) demonstrates the structured and repetitive stages required for designing an integrated water reuse system capable of handling multiple pollutants.

Results And Discussion

cascade table for a single pollutant

The problem data for sources and sinks are presented in Table2 and Table3, respectively, where A: chemical oxygen demand (COD), B: total dissolved solids (TDS), $C_{A,SR}$: concentration of source, F_{SR} : flow rate of source, $Z_{A,SK}$: concentration of sink, and F_{SK} : flow rate of sink.

Table2: Water source and sink data for chemical oxygen demand (COD)

SR_i	F_{SR} (m^3/h)	$C_{A,SR}$ (ppm)	SK_i	F_{SK} (m^3/h)	$Z_{A,SK}$ (ppm)
1	6	8	1	6	3
2	10	6	2	10	3
3	65	13	3	65	5

Table3: Water source and sink data for total dissolved solids (TDS)

SR_i	F_{SR} (m^3/h)	$C_{B,SR}$ (ppm)	SK_i	F_{SK} (m^3/h)	$Z_{B,SK}$ (ppm)
1	6	1000	1	6	400
2	10	870	2	10	450
3	65	1350	3	65	750

Table 4 illustrates the waterfall table methodology, where each pollutant was analyzed individually using the traditional table structure. The data presented in Tables 2 and 3 were used for application purposes.

Table 4: The Water Cascade Table is derived from the data presented in Table 2

The value (44.62) in the first row of column 11 represents the total freshwater target (the required quantity of freshwater), while the same value but in the last row of the same column indicates the total volume of generated wastewater. This represents the targeting step. El-Halwagi et al. (2003) highlighted that the Pinch Point is invariably positioned within one of the source streams, which is identified as the Pinch-causing source. As demonstrated in Table 4, the pinch point is observed at a concentration of (13 ppm).

When dealing with a single pollutant, the recycling plan begins with the cleanest (highest quality) sink using the cleanest source since the sink is the most difficult to fulfill. Depending on the process unit's limitations and the concentration of the pollutant in the water streams, it may be possible to reuse these streams as feed for the process's water demands.

For the purpose of utilizing a water effluent stream. The concentration and flowrate must be kept at or below the current process part's constraints in order to meet a demand in the process. One approach to achieving this is through the use of the K-Nearest Neighbor (KNN) algorithm, originally proposed by Evelyn Fix and Joseph Hodges in 1951. Its theoretical framework was later established by Thomas Cover and Peter Hart in 1967. This algorithm relies on the clustering of basins and sources, taking into account their proximity in concentrations during network design. The K-Nearest Neighbor (KNN) algorithm pinch point is activated to achieve this.

It is very important that the load coming from the source is not higher than the load of the basin, in order to reduce the use of additional clean or freshwater sources to the minimum level. If a source having the same concentration as the basin is available, it is taken as the first choice. Otherwise, the KNN algorithm locates the closest sources and mixes them to get the required concentration. These are the equations that are used to find the flow rates of different sources for mixing and dilution.

Based on data in Table 5, an allocation of $3 m^3/h$ of fresh water and $3 m^3/h$ from SR2 was designated for SK1. Similarly, SK2 received $5 m^3/h$ of fresh water and $5 m^3/h$ from SR2. As for SK3, it was supplied with $36.62 m^3/h$ of fresh water, $2 m^3/h$ from SR2, $6 m^3/h$ from SR1, and $20.38 m^3/h$ from SR3, respectively. It was found that the total amount of fresh water required and the total volume of generated wastewater in this design are equal, both amounting to $44.62 m^3/h$.

Table 5: results from the water pinch analysis, the flow rate is in (m^3/h)

	Sk1	Sk2	Sk3	waste
Freshwater	3	5	36.62	0
SR1	3	5	2	0
SR2	0	0	6	0
SR3	0	0	20.38	44.62

A graphical approach was employed using the concentration composition curve, which demonstrated a clear alignment with the Waterfall Chart results in identifying the pinch point. This correlation is illustrated in the diagrams presented below.

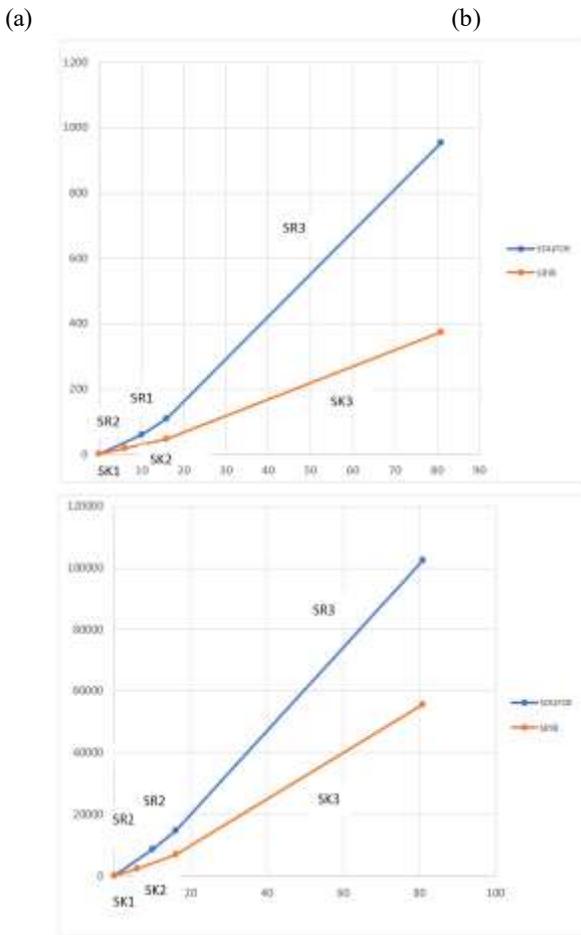


Figure 2: MRPD for the single contaminant example before sliding the source composite curve (a) COD, (b)TDS.

The Material Recovery Pinch Diagram (MRPD) was initially illustrated in Figure 2, where insufficient water was observed due to the sinks having a higher overall flow rate. However, by shifting the source composite curve, the final MRPD was obtained, as shown in Figure 3.

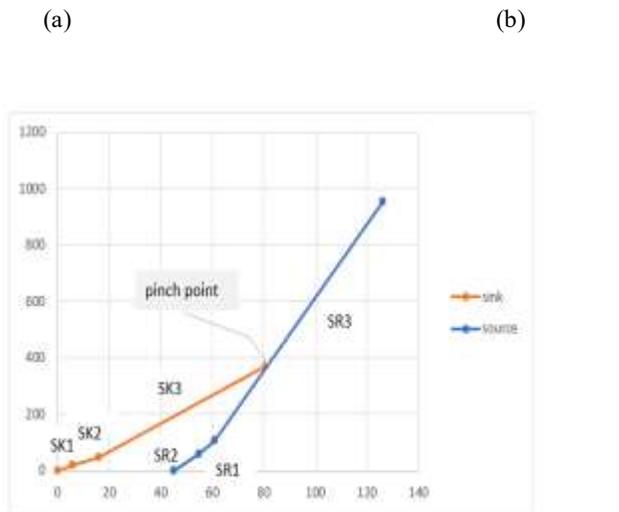


Figure 3: MRPD for the single contaminant example after sliding the source composite curve (a) COD, (b) TDS.

Figure 3 illustrates the location of the pinch point, which occurs at COD and TDS values of 13 ppm and 1350 ppm, respectively. A cascade table is like the sliding of curves described in the last part, but it works with numbers. The Water cascade table can also be applied again, but this time for pollutant B, resulting in the following Tables 6 and 7.

Table 6: The Water Cascade Table is derived from the data presented in Table 3.

	SK_1	SK_2	SK_3	Waste
Fresh water	3.25	5	36.62	0
SR_2	2.75	5	2	0.25
SR_1	0	0	5.98	0.02
SR_3	0	0	20.4	44.6

Table 7: Results from the water pinch analysis, the flow rate is in (m^3/h)

	Sk1	Sk2	Sk3	Waste
Freshwater	3.25	4.83	26.6	0
SR2	2.75	5.17	2.08	0
SR1	0	0	6	0
SR3	0	0	30.32	34.68

Based on data in Table 7, an allocation of $3.25 m^3/h$ of fresh water and $2.75 m^3/h$ from SR2 was designated for SK1. Similarly, SK2 received $4.83 m^3/h$ of fresh water and $5.17 m^3/h$ from SR2. As for SK3, it was supplied with $26.6 m^3/h$ of fresh water, $2.08 m^3/h$ from SR2, $6 m^3/h$ from SR1, and $30.32 m^3/h$ from SR3, respectively. It was found that the total amount of fresh water required and the total volume of generated wastewater in this design are equal, both amounting to $34.68 m^3/h$.

The conclusive flowchart of the water network, predicated on the two pollutants, is illustrated in Figures 4 and 5. The single pollutant technique determined that the minimal freshwater requirement for COD and TDS pollutants was $44.62 m^3/h$ and $34.68 m^3/h$, respectively. Subtracting these figures from the refinery's total water consumption ($175 m^3/h$) indicates that employing the water pinch technique within a single pollutant framework can reduce freshwater consumption by 25% (based on COD) to 19% (based on TDS). The water pinch method diminishes productivity by limiting water consumption and recycling wastewater. Reducing the release of wastewater into the environment by an average of 39%.

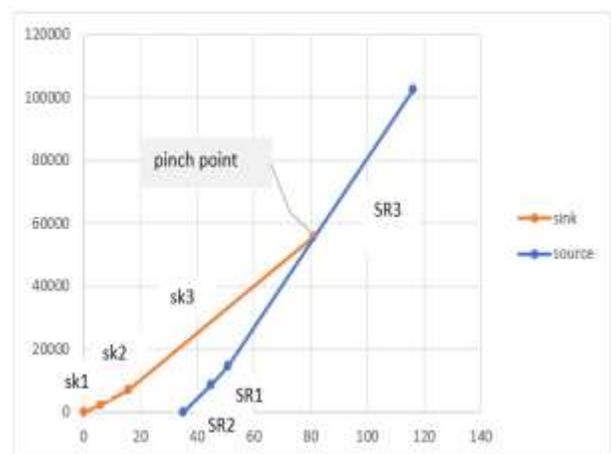


Figure 4: The final flowchart of the water consumption network for COD

Figure 5: The final flowchart of the water consumption network for TDS

ascade table for multiple pollutants

The data presented in Table 8 were extracted from an illustrative example previously introduced in the work of Hashemi, H., Hashemi, F., Young, S., & Rosti, F. (2024).

Table 8: source and sink data

SR_i	F_{SR} (m^3/h)	$C_{A,SR}$ (ppm)	$C_{B,SR}$ (ppm)	SK_i	F_{SK} (m^3/h)	$Z_{A,SK}$ (ppm)	$Z_{B,SK}$ (ppm)
1	6	8	1000	1	6	3	400
2	10	6	870	2	10	3	450
3	65	13	1350	3	65	5	750
FW	-	0	0	-	-	-	-

3.2.1. Scenario 1: Pollutant A as the Limiting pollutant with Sequential Compatibility Testing (A→B).

The process is initiated with pollutant A by constructing a water cascade table to determine both the total fresh water required and the total wastewater generated. The target values for both were found to be 44.62 m^3/h . This outcome can be observed as previously illustrated in the Waterfall Chart for the single pollutant case A, presented in Table 4. The water network for pollutant A was also designed, as presented in Table 5. It is important to note that this design must fulfill the intended objective of the Waterfall Chart approach, which is to ensure that the total amount of fresh water used and the total amount of wastewater generated both equal 44.62 m^3/h . Subsequently, the suitability of these allocations is tested against pollutant B, as illustrated in Table 9 below.

Table 9: Results from the water pinch analysis, the flowrate is in (m^3/h)

Table 9 illustrates the following allocations:

- SK1 was allocated 2.75 m^3/h of SR1, supplemented with 3.25 m^3/h of fresh water.
- SK2 received 5 m^3/h of SR1 and 5 m^3/h of fresh water.
- SK3 was supplied through a mixture of 20.4 m^3/h of SR3, 5.98 m^3/h of SR1, 2 m^3/h of SR2 and 36.62 m^3/h of fresh water.

An increase in the total consumption of fresh water was observed, reaching 44.87 m^3/h , accompanied by a corresponding rise in the total volume of generated wastewater to the same level.

3.2.2. Scenario 2: Pollutant B as the Limiting pollutant with Sequential Compatibility Testing (B→A).

The process is initiated with pollutant B by constructing a water cascade table to determine both the total fresh water required and the total wastewater generated. The target values for both were found to be 34.6 m^3/h . This outcome can be observed as previously illustrated in the Waterfall Chart for the single pollutant case B, presented in Table 6. The water network for pollutant B was also designed, as presented in Table 7. It is important to note that this design must fulfill the intended objective of the Waterfall Chart approach, which is to ensure that the total amount of fresh water used and the total amount of wastewater generated both equal 34.6 m^3/h . Subsequently, the suitability of these allocations is tested against pollutant A, as illustrated in Table 10 below.

Table 10: Results from the water pinch analysis, the flowrate is in (m^3/h)

	SK_1	SK_2	SK_3	Waste
Fresh water	3.25	5	36.58	0
SR_2	2.75	5	2.08	0.17
SR_1	0	0	6	0
SR_3	0	0	20.34	44.66

Table 10 illustrates the following allocations:

- SK1 was allocated 2.75 m^3/h of SR1, supplemented with 3.25 m^3/h of fresh water.
- SK2 received 5 m^3/h of SR1 and 5 m^3/h of fresh water.
- SK3 was supplied through a mixture of 20.34 m^3/h of SR3, 6 m^3/h of SR1, 2.08 m^3/h of SR2 and 36.58 m^3/h of fresh water.

An increase in the total consumption of fresh water was observed, reaching 44.83 m^3/h , accompanied by a corresponding rise in the total volume of generated wastewater to the same level. When comparing Scenarios 1 and 2, the preferred scenario is determined based on the criterion of minimizing total freshwater demand. According to this criterion, Scenario 2 is considered optimal, as pollutant "B" serves as the limiting factor.

The final flowchart of the water consumption network considering both TDS and COD is shown in fig.6 based on the above table (table 10) the amount of freshwater needed in the multi pollutant approach was estimated to be 44.83 m^3/h .

Figure 6: The final flowchart of the consumed water with double pollutant approach (TDS&COD)

A comparative analysis was conducted between the performance of the proposed method for designing an industrial water reuse network - based on the modified water cascade table in the presence of two primary pollutants (A and B) - and the outcomes of an alternative approach that employed the Water Pollutant Analysis (WPA) method, as presented in a case study by Hashemi et al. (2024).

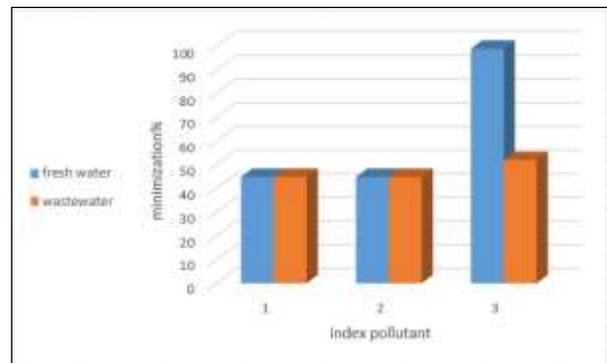


Figure 7 : Chart illustrating the comparison of freshwater consumption and wastewater generation between the proposed method and the reference method. This chart compares three cases of industrial water reuse network design:

- Case 1: Proposed method using contaminant A as the limiting factor
- Case 2: Proposed method using contaminant B as the limiting factor
- Case 3: Reference method using WPA

The proposed method significantly reduced both freshwater consumption and wastewater generation compared to the WPA-based reference.

- Freshwater use dropped from 99 m³/h (WPA) to 44.87 m³/h (Case A) and 44.83 m³/h (Case B)
- Wastewater output decreased from 52 m³/h (WPA) to 44.87 m³/h (Case A) and 44.83 m³/h (Case B)

These results highlight the efficiency of the proposed approach, especially in Case B, which achieved the lowest resource usage while maintaining compliance with contaminant limits.

CONCLUSION

The research showed that the implementation of the newly developed Water Cascade Analysis technique for two simultaneous contaminants (COD and TDS) led to the realization of an optimal design for the water reuse network. This design relies on accurate numerical targeting and meets the concentration constraints for both contaminants. The single-contaminant results pointed out a substantial decrease in fresh water intake, reaching 44.62 m³/h for COD and 34.68 m³/h for TDS, which accounts for a decrease that varies between 19% and 25% of the refinery's total consumption.

The sequential analysis continued to demonstrate that choosing TDS as the limiting contaminant results in the minimum freshwater consumption possible in a multi-contaminant system, quantified as 44.83 m³/h, the wastewater quantity being equal to that value. The comparison of the proposed method with the reference WPA methodology unfolded that this approach leads to a reduction in freshwater usage by more than 55% (from 99 to about 45 m³/h) and also a similar reduction in wastewater discharge (from 52 to about 44.8 m³/h).

Such outcomes reaffirm that the suggested Multi-Pollutant WCA approach offers a high degree of precision and ease of application. It goes beyond traditional design methods in terms of operational efficiency and reduction of environmental impact, thus it is a plausible option for process engineering applications at refineries and industrial facilities with complex water networks.

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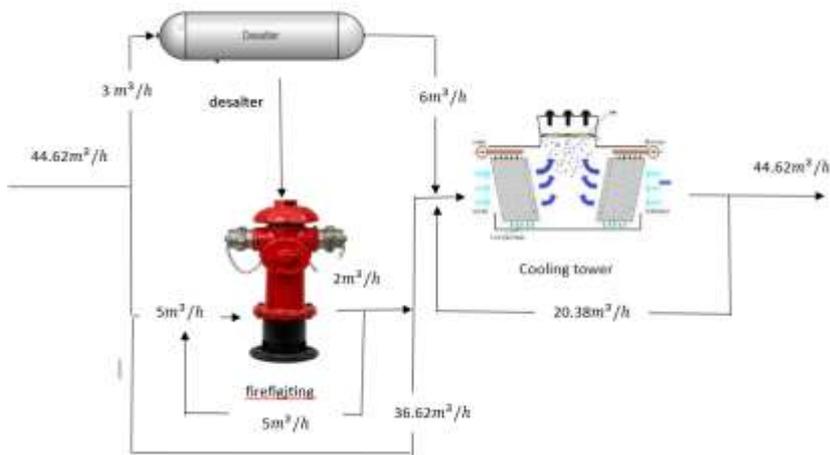
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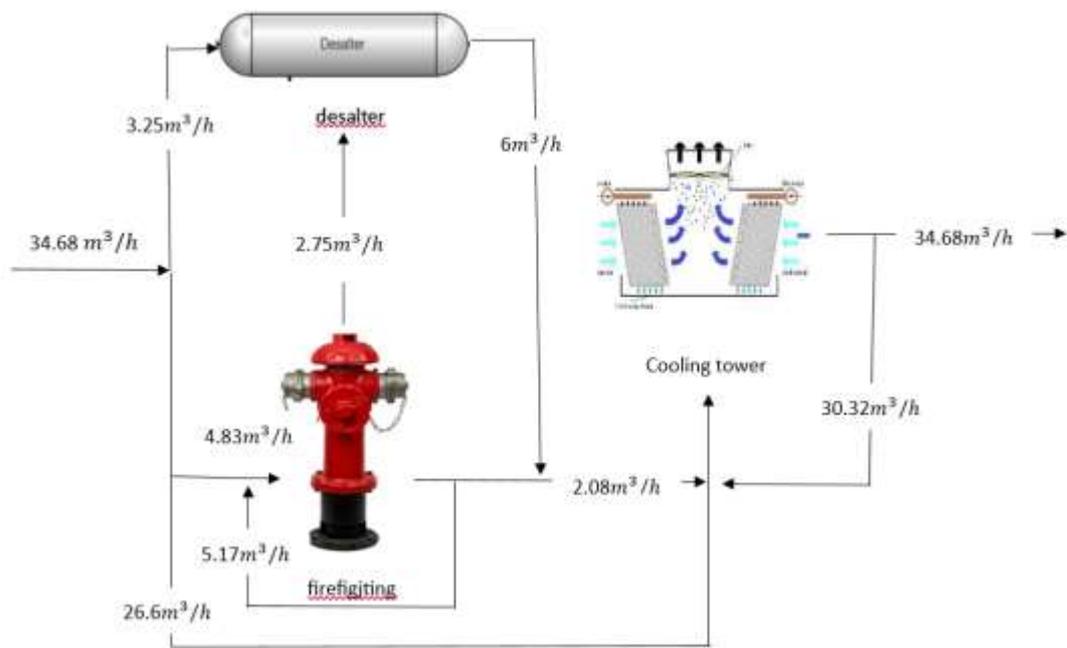
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Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
Conc. C_{ni} (ppm)	$\Delta C_n = C_{n+1} - C_n$ (ppm)	ΣF_{SRi} (kg/h)	ΣF_{ski} (kg/h)	$\Sigma F_{SRi} - \Sigma F_{ski}$	$F_{cum.}$	$\Delta load = F_{cum.n} * \Delta C_n$ (kg/h)	$Cum. load = cum. load_{n-1} + \Delta load_{n-1}$ (kg/h)	$Cumfresh_n = \frac{cumload_n}{cn-cfw}$
					$F_{cum.} = 0$ (freshwater)			
C_1		$\Sigma F_{SR1.C_1}$	$\Sigma F_{sk1.C_1}$	$\Sigma F_{SR1.C_1} - \Sigma F_{sk1.C_1}$			0	0
	$C_2 - C_1$				$F_{cum.1}$	$F_{cum.1} * (C_2 - C_1)$		
C_2		$\Sigma F_{SR2.C_2}$	$\Sigma F_{sk2.C_2}$	$\Sigma F_{SR2.C_2} - \Sigma F_{sk2.C_2}$			$cum. load_2$	$Cumfresh_2$
	$C_3 - C_2$				$F_{cum.2}$	$F_{cum.2} * (C_3 - C_2)$		
C_3		$\Sigma F_{SR3.C_3}$	$\Sigma F_{sk3.C_3}$	$\Sigma F_{SR3.C_3} - \Sigma F_{sk3.C_3}$			$cum. load_3$	$Cumfresh_3$
	$C_n - C_3$				$F_{cum.3}$	$F_{cum.3} * (C_4 - C_3)$		
C_n		$\Sigma F_{SRn.C_n}$	$\Sigma F_{skn.C_n}$	$\Sigma F_{SRn.C_n} - \Sigma F_{skn.C_n}$			$cum. load_n$	$Cumfresh_n$
	$C_{n+1} - C_n$				$F_{cum.n}$	$F_{cum.n} * (C_{n+1} - C_n)$		
C_{n+1}		$\Sigma F_{SR_{n+1}.C_{n+1}}$	$\Sigma F_{sk_{n+1}.C_{n+1}}$	$\Sigma F_{SR_{n+1}.C_{n+1}} - \Sigma F_{sk_{n+1}.C_{n+1}}$			$cum. load_{n+1}$	$Cumfresh_{n+1}$

C_n	ΔC_n	ΣF_{sk}	ΣF_{SR}	$\Sigma F_{SR} - \Sigma F_{sk}$	ΣF_{sk}	Δm_n	Cum. Δm	$F_{sk,k}$	$F_{c,k}$	Δm_n	cum. Δm_n	$F_{sk,k}$
					0				34.67			
0	400	0	0	0	0	0		34.67	13866.67			
400	50	6	0	-6	-6	-300	0	0	28.67	1433.333333	13866.67	34.6667
450	300	10	0	-10	-16	-4800	-300	-0.667	18.67	5600	15300.00	34
750	120	65	0	-65	-81	-9720	-5100	-6.8	-46.33	-5560	20900.00	27.8667
870	130	0	10	10	-71	-9230	-14820	-17.034	-36.33	-4723.333333	15340.00	17.6322
1000	350	0	6	6	-65	-22750	-24050	-24.05	-30.33	-10616.6667	10616.67	10.6167
1350	998650	0	65	65	0	0	-46800	-34.666667	34.67	34619866.67	0.00	
1000000		0	0	0	0	0	-46800	-0.0468			34619866.67	





C_k	ΔC_k	ΣF_{ski}	ΣF_{SRI}	$\Sigma F_{SRI} - \Sigma F_{ski}$	$\Sigma F_{c,k}$	Δm_k	Cum. Δm	$F_{Fw,k}$	$F_{c,k}$	Δm_k	cum. Δm_k	$F_{Fw,k}$
					0				44.62			
0		0	0	0	0	0			44.62	133.85		
3	3	16	0	-16	0	0		0	44.62	133.85	133.85	44.6154
	2				-16	-32			28.62	57.23076923		
5	5	65	0	-65			-32	-6.400			191.08	38.2154
	1				-81	-81			-36.38	-36.3846154		
6	6	0	10	10			-113	-18.833333			154.69	25.7821
	2				-71	-142			-26.38	-52.7692308		
8	8	0	6	6			-255	-31.875			101.92	12.7404
	5				-65	-325			-20.38	-101.923077		
13	13	0	65	65			-580	-44.615385			0.00	0
	999987				0	0			44.62	44614804.62		
1000000		0	0	0			-580	-0.00058			44614804.62	

