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Design of Wastewater Treatment System of Multiple Contaminants: Integrating Environmental Considerations for Sustainable Development

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Abstract

Wastewater treatment is essential for protecting the environment and human health because it removes hazardous pollutants. In line with Egypt's Vision 2030, this study proposes a new approach to the design of distributed wastewater treatment networks, to reduce pollution discharge into the environment.The two main parts of the proposed strategy are as follows: first, treatment units are prioritized for implementation by giving lower flow rate units priority; second, the pinch method is employed to identify which streams should be treated in each unit.In the three case studies, the maximum allowable environmental limit concentration was set at 10 ppm, and the removal ratio for the treatment plants (TP) was set at 99%. The results show that, in case study one, the flow rates of TP_1, TP_2, and TP_3 are 39.53 t/h, 38.89 t/h and 37.22, respectively. In case study two, the flow rates of TP_1, TP_2, TP_3, TP_4, TP_5, and TP_6 are 56.32 t/h, 54.64 t/h, 55.15 t/h, 55.55 t/h, 56.81 t/h, and 26.64 t/h, respectively. In case study three, the flow rates of TP_1, TP_2, TP_3, TP_4, TP_5, and are 323.11 t/h, 107.10 t/h, 328.67 t/h,308.50t/h, and 248.57 t/h respectively. Based on these results, the discharge of contaminants into the environment at a concentration of 10 ppm was achieved.

Keywords: Pinch Method;Wastewater Treatment; Multiple Contaminant; Process Synthesis.

1. Introduction

Egypt Vision 2030 is a national policy that seeks to achieve sustainable development by balancing economic growth, social fairness, and environmental sustainability[1,2]. Wastewater management is an essential component of this vision, as it addresses water scarcity, public health, and environmental challenges. The increasing amount of wastewater discharge and more stringent environmental restrictions over the last 20 years have made the integration of wastewater treatment systems a vital sector of focus in water resource management. When wastewater streams are separated for individual treatment as needed, distributed wastewater treatment offers a number of benefits over centralized systems, such as increased flexibility, scalability to meet local needs, lower capital and maintenance costs, fewer infrastructurerequirements.While wastewater treatment network design has received a lot of attention, with many studies concentrating on reducing the flow of wastewater streams treated by each unit, comparatively few have examined network design from the standpoint of reducing pollutant concentrations in environmental discharges. Significant ecological concerns, such as the long-term deterioration of environmental systems, arise from the buildup of such contaminants. In order to close this gap and promote more sustainable wastewater treatment techniques, this study suggests a design strategy that not only lowers the concentration of released contaminants but also lessens their buildup in natural ecosystems.

The main techniques for integrating decentralized wastewater treatment plants are mathematical programming and pinch analysis approaches. Simple multi-contaminant wastewater treatment networks (WWTNs) can be synthesized using the Water Pinch Analysis method, which was first presented by Y. P. Wang. et al. [3]. They started by building a subnetwork for every pollutant, then merged these subnetworks to produce the final system. W. C. J. Kuo, et al. [4], however, pointed out a possible problem with this combination process, highlighting that it can cause wastewater deterioration, which would raise the treatment flow rates in subsequent procedures. They developed the idea of mixing exergy loss to measure the degree of wastewater degradation in order to address this.

A targeted process for the complete water system, including wastewater treatment, regeneration, and water reuse, was created by D. K. S. Ng, et al. [5, 6]. They used both algebraic and graphical techniques to investigate the relationships between different system components. S. Bandyopadhyay [7] used graphical and algebraic techniques to determine the lowest

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treatment flow rate for flow-loss systems. S. S. T. Soo, et al. [8] used the wastewater composite curve (WCC) to examine many treatment methods for one or two pollutants.

One among the main goals of designing decentralized wastewater treatment networks (WTNs) is to lower the overall treatment flow rate. Unnecessary merging of wastewater streams raises a WTN system's overall treatment flow rate, as Liu et al. realized. A number of novel techniques were presented in light of this realization. The total treatment flow rate potential (TTFP), which Z. Liu, et al. proposed, helps decide the order of treatment procedures by reflecting the minimum flow rate needed to achieve environmental constraints [9].Z. H. Liu, et al. employed pinch analysis to determine the smallest treatment flow rate for each procedure and created heuristic criteria to determine the process sequence [10]. The total mixing influence potential (TMIP) was put out by A. Li, et al. as a numerical metric to evaluate how stream mixing affects a WTN's overall treatment flow rate. In the design, the process with the lowest TMIP value is given priority. With this method, complicated issues can be effectively resolved by utilizing the numerical indication [11].

Using mathematical programming techniques is crucial for combining wastewater treatment networks (WTNs) with multiple contaminants. A superstructure comprising water-using and wastewater-treatment units as well as a sophisticated solution method was created by N. Takama, et al. [12]. A sequential relaxation process was presented byB. Galan, et al. [13] to solve nonlinear models for distributed WTN system design, P. M. Castro, et al. [14,15] developed a two-stage technique for designing dispersed wastewater networks with multiple pollutants. B. H. Li, et al.[16] created an effective initialization technique for solving NLP and MINLP models in water networks with different pollutants. F. B. Gabriel, et al. [17] created an optimization method that considers wastewater treatment and cost functions while optimizing water recycling and reuse.Y. J. Liu, et al[18] effectively solved NLP and MINLP models for wastewater treatment network design using a particle swarm optimization technique, overcoming non-convexity issues and accomplishing efficient global optimization without the need for an initial point.A. Alva-Argaéz, et al. [19] introduced a unique decomposition method that simplifies the optimization issue by using water pinch insights to define consecutive projections in the solution space, M. L. Bergamini, et al.[20] utilized a global optimization approach. Furthermore, the ideal design of reverse osmosis WTNs was the attention ofR.Karuppiah, et al. [21] and Y. Saif, et al. [22, 23]. S. R. Lim, et al. studied the compromise between ecosystem effect and financial expenses in the synthesis of wastewater treatment systems [24, 25].

A. Quaglia, et al. tackled intricate industrial design issues pertaining to wastewater treatment and reuse networks by combining optimization techniques with wastewater engineering ideas [26]. O. Burgara-Montero, et al. used discretization optimization to solve a multiobjective programming model[27]. G. Statyukha, et al. developed a superstructurusing pinch analysis and wastewater deterioration, and proposed astraightforward but effective optimization approach.[28]. S. Y. Alnouri, et al. proposed optimal design solutions for interplant water networks in an industrial metropolis, including both centralized and decentralized treatment options[29]. Retrofit techniques for WTNs in industrial parks were also covered byE. Rubio-Castro, et al. [30].

The development of innovative methods for removing heavy metals and other dangerous and poisonous substances from wastewater is now part of the goal of environmental preservation, which has grown beyond the planning of wastewater treatment networks. Recent wastewater treatment literature emphasizes the growing complexity and urgency of managing different industrial and municipal effluents that contain a multitude of often harmful chemicals. Studies on oil refinery wastewater, textile wastewater, wastewater containing copper, and general industrial wastewater draw attention to the drawbacks of traditional single-treatment systems, which are often inefficient, cost a lot of energy, or have an adverse impact on the environment. In order to address these issues, recent advancements have focused on sustainable and integrated treatment strategies, such as combining biological and physicochemical methods, applying membrane technologies with anti-fouling modifications, and installing energy recovery and renewable energy systems [31,32,33,34]. Currently, long-term sustainability, pollutant-specific removal, and environmental preservation are prioritized over cost-cutting or operational efficiency alone. In order to ensure that wastewater treatment meets ecological and public health goals in addition to regulatory compliance, researchers also support lifespan assessments, intelligent system optimization, and techno-economic studies [35,36,37].

This work focuses on compliance with environmental standards and regulations by enhancing the efficiency of wastewater treatment processes and reducing the maximum allowable concentration of pollutant discharge into the environment. It primarily employs the pinch analysis method to identify streams that require full or partial treatment and those that do not need treatment. Unlike previous methods, this approach aims to minimize the pollutant load discharged into the environment, regardless of the flow rate of the treatment units[38].

This paper focuses on designing wastewater treatment systems with pollutant discharge concentrations below the limits set by the Egyptian Environmental Affairs Agency (EEAA). As shown in Table 1, the maximum allowable concentration limits for some pollutants will be used in designing our wastewater treatment systems. The objective is to comply with increasingly tough environmental rules and regulations, which are projected to tighten further while lowering flow rates as much as possible.

Table 1: The maximum allowable concentrations of a specific contaminants in wastewater discharge, as specified by (EEAA).

Contaminants	**EEAA Limit*(ppm)**
Biochemical Oxygen Demand(BOD)	60
Chemical Oxygen Demand(COD)	100
Oil and Grease	15
Total Suspended Solids(TSS)	60
Nitrates(NO_3^-)	40
Total Dissolved Solids(TDS)	2000

*Egyptian Environmental Affairs Agency (EEAA). **(1994).** ***Environmental Law No. 4 of 1994 and its amendments[39].***

2. Materials and Methods

2.1 Problem Statement

A set of wastewater streams with known concentrations of various pollutants is available, as well as a variety of treatment units designed to selectively remove certain pollutants. To maintain compliance with environmental standards, it is essential to design an optimal treatment system capable of efficiently addressing these contaminants. In the three case studies, we designed the wastewater treatment networks to consistent with Egypt's Vision 2030, which prioritizes sustainable water management, environmental protection, and resource efficiencies.

2.2 Design Methodology

Step 1:Determine the main Pollutant

The main contaminant targeted by each treatment plant must be clearly defined and thoroughly characterized to ensure effective treatment.

Step 2:Compute the lowest Flow Rate for Single pollutant

Compute the smallest flow rate required to eliminate a particular contamination from a single stream using Equation (1). To get the total minimum flow rate needed for the treatment plant to eliminate the contamination from all streams, add up the flow rates that have been determined for each stream.

$$F_{i,j}^{k} = F_i * (C_{i,j}^{in} - C_{env,j}^{lim})/(C_{i,j}^{in} * RR) \quad (1)$$

Step 3:Arrangethe wastewaterTreatment units

The lowest flow rates for each treatment unit are calculated, with priority given to processes that require the lowest total flow rate for execution.

Step 4:Identify the Minimum Removal mass Load

In each treatment unit, rank the streams by pollutant j concentration, from highest to lowest. Next, apply Equation (2) to calculate the minimum required removal mass load.

$$M_j^{rem} = \sum \text{mi}, -C_{env,j}^{lim} \sum f_i \quad (2)$$

where: ($m_{i,j}=f_i * c_{i,j}$)

Step 5:Determine the Pinch Stream

Identify the wastewater stream that is either partially treated, totally bypassed, or fully treated (pinch stream)the stream that governs the limiting removal condition using Equation (3)**.**

$$\sum_{i=1}^{p-1} m_{i,\ j} < M_{TPk,j} \le \sum_{i=1}^{p} m_{i,j} \quad (3)$$

where: $M_{TPk,j}=M_j^{rem}/RR_j$

Step 6:Compute the Pinch Stream Flow Rate

For the pinch stream, determine the flow rate that should be treated using Equation (4) and the flow rate that should be bypassed using Equation (5).

$$f_{TPK,pt} = (M_{TPK,i} - \sum_{i=1}^{p} m_{i,j})/C_{p,j} \quad (4)$$

$$f_{TPK,pb} = f_p - f_{TPK,pt} \quad (5)$$

Step 7:Determine Minimum Treatment Flow Rate

Compute the lowest treatment flow rate required for the treatment unitusing the equation (6), which considers the cumulative flow rate of all streams above the pinch point.

$$F_{TPk} = f_{TPk,pt} + \sum f_i \quad (6)$$

where: $\sum F_i$ is all streams' flow rate above the pinch stream.

The design methodology for a wastewater treatment system that targets particular contaminants. are summarized and illustrated in the figure 1. A treatment system's design can be optimized using this methodical process to efficiently meet environmental criteria while using the fewest resources possible.

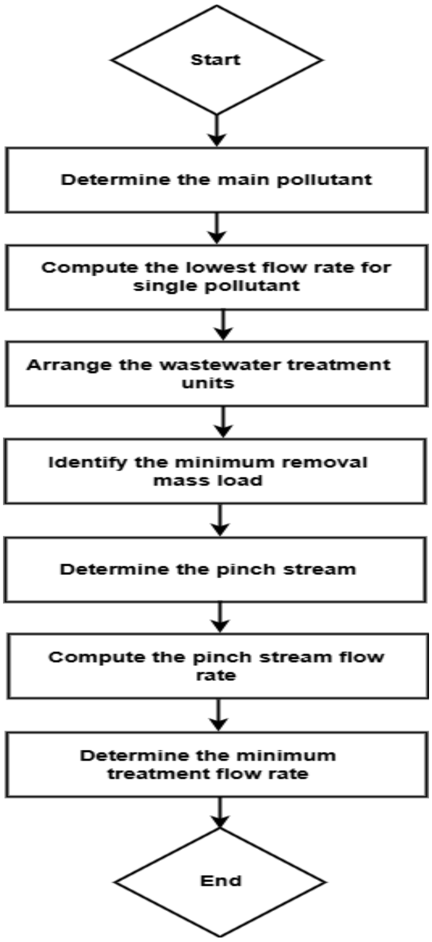

Figure 1.The flowchart proposed for designing the wastewater treatment systems.

3. The Case Studies

3.1 Case Study One

Table 2 outlines the flow rates and pollutant concentrations in the waste streams, while Table 3 shows the details of treatment plant data. The maximum allowable environmental concentrations for the pollutants COD, BOD, and Oil are set at 10 ppm. For simplicity, COD is designated as pollutant A, BOD as pollutant B, and Oil as pollutant C [11].

Table 2: The flow rates and pollutants concentration (Case Study One).

Stream	Flow rate (t/h)	Concentration (ppm)		
		COD	BOD	Oil
S_1	20.00	600.00	500.00	500.00
S_2	15.00	400.00	200.00	100.00
S_3	5.00	200.00	1000.00	200.00

Table 3: The removal ratios for treatment plants (Case Study One).

Process	Removal Ratio (%)		
	COD	BOD	Oil
TP_1	99.00	0.00	0.00
TP_2	0.00	99.00	0.00
TP_3	0.00	0.00	99.00

Step1:
Identify which pollutant is the main one for each treatment unit: for TP_1, the targeted pollutant is pollutant A; for TP_2, it is pollutant B; and for TP_3, it is pollutant C.
Step2:
Determine the flow rate necessary in a given stream (i) to eliminate a specific pollutant (j). Equation (1) is used to compute the total lowest flow rates that each treatment unit must achieve in order to eliminate the contaminant from all streams, and these values are displayed in Table 4.

Table 4:The TP_1, TP_2, and TP_3 flow rate values (Case Study One).

TP_1		TP_2		TP_3	
Flow Rate(t/h)	A	Flow Rate(t/h)	B	Flow Rate(t/h)	C
$F^1_{1,A}$	19.87*	$F^2_{1,B}$	19.79	$F^3_{1,C}$	19.79
$F^1_{2,A}$	14.77	$F^2_{2,B}$	14.39	$F^3_{2,C}$	13.64
$F^1_{3,A}$	4.80	$F^2_{3,B}$	5	$F^3_{3,C}$	4.80
$\sum F^1_{T,A}$	39.44	$\sum F^2_{T,B}$	39.18	$\sum F^3_{T,C}$	38.23

Using Equation (7), the flow rate necessary to eliminate a pollutant load from a given stream is demonstrated below:

$$*F^1_{1,A} = \frac{20(600-10)}{600*0.99} = 19.87 \qquad (7)$$

Step 3:
As shown in Table 4, the process sequence follows the order of TP_3, TP_2, and TP_1, prioritizing the process with the minimum flow rate to be carried out first.
Step 4:
Equation (2) is used to compute the minimal removal mass load for all pollutants using the figures in Tables 5, 6, and 7.

Table 5: Determining the pinch stream for TP_3 to eliminate the pollutant C (Case Study One).

Stream	F_i (t/h)	$C_{i,C}$(ppm)	$m_{i,C}$ (g/h)	$\sum m_{i,C}$ (g/h)
S_1	20.00	500.00	10000.00	10000.00
S_3	5.00	200.00	1000.00	11000.00
S_2	15.00	100.00	1500.00	12500.00
sum	40.00		12500.00	

Table 6: Determining the pinch stream for TP_2 to eliminate the pollutant B (Case Study One).

Stream	F_i (t/h)	$C_{i,B}$(ppm)	$m_{i,B}$ (g/h)	$\sum m_{i,B}$ (g/h)
S_{m1}	37.22	468.67	17443.90	17443.90
S_2	2.78	200.00	556	17999.90
Sum	40.00		17999.90	

Table 7: Determining the pinch stream for TP_1 to eliminate the pollutant A (Case Study One).

Stream	F_i (t/h)	$C_{i,A}$ (ppm)	$m_{i,A}$ (g/h)	$\sum m_{i,A}$ (g/h)
S_{m2}	38.89	477.14	18555.97	18555.97
S_2	1.11	400.00	444	18999.97
sum	40.00		18999.97	

The smallest mass loads that need to be eliminated, considering the discharged pollutant concentration of 10 ppm, are computed using Equation (1) and the figures from Tables 5, 6, and 7.

The results are as follows: M_C^{rem} =12100 g/h, M_B^{rem} =1 7599.90g/h, and M_A^{rem} = 18 599.97g/h

Step 5:
Utilizing Equation (3), the mass load at TPk's entrance and the relevant pinch streams are computed and briefed in Table 8.

Table 8: Contaminant Types and Their Mass Loads at Treatment unit entrance and Pinch Stream (Case Study One).

Contaminant	TP_k	M_{TP_k}	Pinch stream
A	1	18787.85	S_2
B	2	17777.68	S_2
C	3	12222.22	S_2

Step 6:
The following values are obtained by applying Equations (4) and (5) to determine the pinch stream portions that require treatment and bypass: $F_{TP_{1,pt}} = 0.64$ t/h $F_{TP_{1,pb}} = 0.47$ t/h, $F_{TP_{2,pt}} = 1.67$ t/h $F_{TP_{2,pb}} = 1.11$ t/h, $F_{TP_{3,pt}} = 12.22$ t/h, and $F_{TP_{3,pb}} = 2.78$ t/h

Step 7:
The smallest treatment flow rates for each treatment unit are computed using Equation (6). The results are as follows: $F_{TP_1} = 39.53t/h$, $F_{TP2} = 38.89t/h$, and $F_{TP3} = 37.22t/h$, Figure 2 The final proposed design network is based on the design steps outlined in this paper.

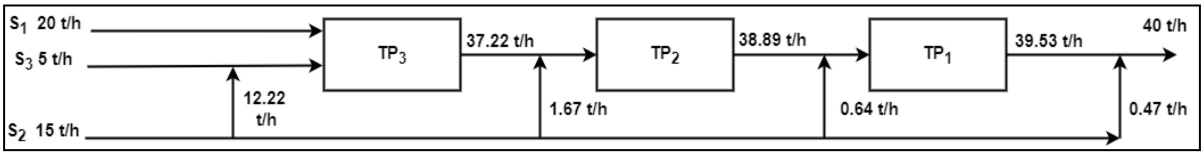

Figure 2. The final proposed design network (Case Study One)

3.2 Case Study Two

Table 9 outlines the flow rates and pollutant concentrations in the waste streams, while Table 10 shows the details of treatment plant data. The maximum allowable environmental concentrations for the pollutants BOD, TSS, COD, NO_3^-, TDS and Oil are set at 10 ppm. For simplicity, BOD is designated as pollutant A, TSS as pollutant B, COD as pollutant C, NO_3^- as pollutant D, TDS as pollutant E, and Oil as pollutant F [11].

Table 9: The flow rates and pollutant concentrations (Case Study Two).

Stream	Concentration (ppm)						Flow Rate (t/h)
	BOD	TSS	COD	NO_3^-	TDS	Oil	
S_1	1100.00	500.00	500.00	200.00	800.00	100.00	19.00
S_2	40.00	0.00	100.00	300.00	910.00	200.00	7.00
S_3	200.00	220.00	200.00	500.00	150.00	0.00	8.00
S_4	60.00	510.00	500.00	200.00	780.00	100.00	6.00
S_5	400.00	170.00	100.00	300.00	900.00	0.00	17.00

Table 10: The removal ratios for the treatment plants (Case Study Two).

Process	Removal Ratio (%)					
	BOD	TSS	COD	NO_3^-	TDS	Oil
TP_1	99.00	0.00	0.00	0.00	0.00	0.00
TP_2	0.00	99.00	0.00	0.00	0.00	0.00
TP_3	0.00	0.00	99.00	0.00	0.00	0.00
TP_4	0.00	0.00	0.00	99.00	0.00	0.00
TP_5	0.00	0.00	0.00	0.00	99.00	0.00
TP_6	0.00	0.00	0.00	0.00	0.00	99.00

Step 1:
Identify which pollutant is the main one for each treatment unit: for TP_1, the targeted pollutant is pollutant A; for TP_2, it is pollutant B ; for TP_3, it is pollutant C; for TP_4, it is pollutant D; for TP_5, it is pollutant F; and for TP_6, it is pollutant E.

Step 2:
Determine the flow rate necessary in a given stream (i) to eliminate a specific pollutant (j). Equation (1) is used to compute the total lowest flow rates that each treatment unit must achieve in order to eliminate the contaminant from all streams, and these values are displayed in Table 11 and Table 12.

Table 11: The TP_1, TP_2, and TP_3 flow rate values (Case Study Two).

TP_1		TP_2		TP_3	
Flow Rate(t/h)	**A**	**Flow Rate(t/h)**	**B**	**Flow Rate(t/h)**	**C**
$F^1_{1,A}$	19.02	$F^2_{1,B}$	18.81	$F^3_{1,C}$	18.81
$F^1_{2,A}$	5.30	$F^2_{2,B}$	---	$F^3_{2,C}$	6.36
$F^1_{3,A}$	7.68	$F^2_{3,B}$	7.71	$F^3_{3,C}$	7.68
$F^1_{4,A}$	5.05	$F^1_{4,B}$	5.94	$F^1_{4,C}$	5.94
$F^1_{5,A}$	16.74	$F^1_{5,B}$	16.16	$F^1_{5,C}$	15.45
$\sum F^1_{T,A}$	53.79	$\sum F^2_{T,B}$	48.62	$\sum F^3_{T,C}$	54.24

Table 12: The TP_4, and TP_5 flow rate values (Case Study Two).

TP_4		TP_5		TP_6	
Flow Rate(t/h)	**D**	**Flow Rate(t/h)**	**E**	**Flow Rate(t/h)**	**F**
$F^4_{1,D}$	18.23	$F^5_{1,E}$	18.95	$F^6_{1,F}$	17.27
$F^4_{2,D}$	6.84	$F^5_{2,E}$	6.99	$F^6_{2,F}$	6.72
$F^4_{3,D}$	7.92	$F^5_{3,E}$	7.54	$F^6_{3,F}$	---
$F^4_{4,D}$	5.76	$F^5_{4,E}$	5.98	$F^6_{4,F}$	5.45
$F^4_{5,D}$	16.59	$F^5_{5,E}$	16.98	$F^6_{5,F}$	---
$\sum F^4_{T,D}$	55.34	$\sum F^5_{T,E}$	56.44	$\sum F^6_{T,F}$	29.44

Step 3:
As shown in Tables 11 ,12 the process sequence follows the order of TP_6, TP_2, TP_1, TP_3, TP_4 and TP_5 prioritizing the process with the minimum flow rate to be carried out first.

Step 4:
Equation (2) is used to compute the minimal removal mass load for all pollutants using the figures in Tables 13, 14,15,16,17 and 18.

Table 13: Determining the pinch stream for TP_6 to eliminate the pollutant F (Case Study Two).

Stream	F_i (t/h)	$C_{i,F}$(ppm)	$m_{i,F}$ (g/h)	$\sum m_{i,F}$ (g/h)
S_2	7.00	200.00	1400.00	1400.00
S_1	19.00	100.00	1900.00	3300.00
S_4	6.00	100.00	600.00	3900.00
S_3	8.00	0.00	0.00	3900.00
S_5	17.00	0.00	0.00	3900.00
sum	57.00		3900.00	

Table 14: Determining the pinch stream for TP_2 to eliminate the pollutant B (Case Study Two).

Stream	F_i (t/h)	$C_{i,B}$ (ppm)	$m_{i,B}$ (g/h)	$\sum m_{i,B}$ (g/h)
S_4	5.36	510	2733.60	2733.60
S_{m1}	26.64	368.86	9826.43	12560.03
S_3	8	220	1760	14320.03
S_5	17	170	2890	17210.03
sum	57.00		17210.03	

Table 15: Determining the pinch stream for TP_1 to eliminate the pollutant A (Case Study Two).

Streams	F_i (t/h)	$C_{i,A}$(ppm)	$m_{i,A}$ (g/h)	$\sum m_{i,A}$ (g/h)
S_{m2}	54.64	530.68	28996.36	28996.36
S_5	2.36	400.00	944	29940.36
sum	57.00		29940.36	

Table 16: Determining the pinch stream for TP_3 to eliminate the pollutant C (Case Study Two).

Stream	F_i (t/h)	$C_{i,C}$(ppm)	$m_{i,C}$ (g/h)	$\sum m_{i,C}$ (g/h)
S_{m3}	56.32	291.76	16431.92	16431.92
S_5	0.68	100.00	68	16499.92
sum	57.00		16499.92	

Table 17: Determining the pinch stream for TP_4 to eliminate the pollutant D (Case Study Two).

Stream	F_i (t/h)	$C_{i,D}$(ppm)	$m_{i,D}$ (g/h)	$\sum m_{i,D}$ (g/h)
S_5	0.68	300	204	204
S_{m3}	1.17	284.02	332.30	536.30
S_{m4}	55.15	284.02	15663.70	16200
sum	57.00		16200	

Table 18: Determining the pinch stream for TP_5 to eliminate the pollutant E (Case Study Two).

Stream	F_i (t/h)	C_E (ppm)	$m_{5,E}$ (g/h)	$\sum m_{5.E}$ (g/h)
S_{m5}	55.55	750.04	41664.72	41664.72
S_{m4}	1.45	748.19	1084.88	42749.60
sum	57		42749.60	

The smallest mass loads that need to be eliminated, considering the discharged pollutant concentration of 10 ppm, are computed using Equation (1) and the figures from Tables 13, 14,15,16,17 and 18.The results are as follows: M_C^{rem}=15929.92 g/h, M_B^{rem}=16640.03 g/h, M_A^{rem}= 29370.36 g/h M_E^{rem}=42179.60 g/h, M_F^{rem}=3330 g/h, and M_D^{rem} =15630 g/h

Step 5:

Utilizing Equation (3), the mass load at TPk's entrance and the relevant pinch streams are computed and briefed in Table 19.

Table 19: Contaminant Types and Their Mass Loads at Treatment unit entrance and Pinch Stream (Case Study Two).

Contaminant	TP_k	M_{TP_k}	Pinch stream
A	1	29667.03	S_2
B	2	16808.11	S_5
C	3	16090.83	S_{m3}
D	4	15787.88	S_{m4}
E	5	42605.65	S_{m4}
F	6	3363.64	S_4

Step 6:

The following values are obtained by applying Equations (4) and (5) to determine the pinch stream portions that require treatment and bypass: $F_{TP_{1,pt}} = 1.68$ t/h, $F_{TP_{1,pb}} = 0.68$ t/h, $F_{TP_{2,pt}} = 14.64$ t/h, $F_{TP_{2,pb}} = 2.36$ t/h, $F_{TP_{3,pt}} = 55.15$ t/h, $F_{TP_{3,pb}} = 1.17$ t/h, $F_{TP_{4,pt}} = 53.70$ t/h, $F_{TP_{4,pb}} = 1.45$ t/h, $F_{TP_{5,pt}} = 1.26$ t/h, $F_{TP_{5,pb}} = 0.19$ t/h, $F_{TP_{6,pt}} = 0.64$ t/h,and $F_{TP_{6,pb}} = 5.36$ t/h.

Step 7:

The lowest treatment flow rates for each treatment plant are computed using Equation (6). The results are as follows: $F_{TP_1} = 56.32t/h$, $F_{TP2} = 54.64t/h$, $F_{TP3} = 55.15t/h$, $F_{TP4} = 55.55h$, $F_{TP5} = 56.81t/h$,and $F_{TP6} = 26.64t/h$ .Figure 3 The final proposed design network is based on the design steps outlined in this paper.

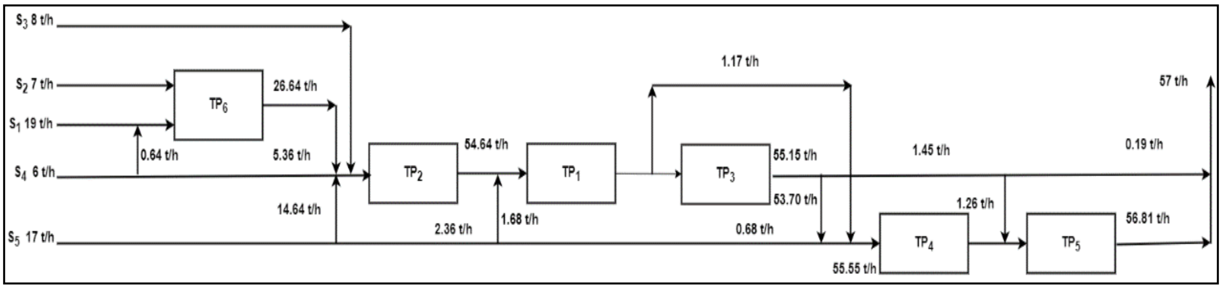

Figure 3. The final proposed design network (Case Study Two).

3.3 Case Study Three

Table 20 outlines the flow rates and pollutant concentrations in the waste streams, while Table 21 shows the details of treatment plant data. The maximum allowable environmental concentrations for the pollutants BOD, TSS, COD, NO_3^-, and P are set at 10 ppm. For simplicity, BOD is designated as pollutant A, TSS as pollutant B, COD as pollutant C, NO_3^- as pollutant D, and TDS as pollutant E [11].

Table 20: Flow rates and pollutant concentrations (Case Study Three)

Stream	Concentration (ppm)					Flow rate(t/h)
	BOD	TSS	COD	NO_3^-	TDS	
S_1	100.00	50.00	350.00	0.00	70.00	36.00
S_2	600.00	800.00	1500.00	0.00	910.00	24.00
S_3	900.00	0.00	600.00	150.00	230.00	15.00
S_4	10.00	10.00	100.00	3000.00	850.00	25.00
S_5	40.00	170.00	0.00	500.00	690.00	18.00
S_6	0.00	1100.00	0.00	200.00	340.00	35.00
S_7	120.00	10.00	500.00	2000.00	70.00	9.00
S_8	370.00	20.00	100.00	30.00	690.00	2.00
S_9	900.00	350.00	200.00	80.00	230.00	3.00
S_{10}	250.00	270.00	90.00	0.00	580.00	23.00
S_{11}	0.00	1190.00	60.00	230.00	370.00	89.00
S_{12}	0.00	0.00	20.00	800.00	100.00	1.00
S_{13}	2000.00	600.00	340.00	0.00	30.00	5.00
S_{14}	0.00	5.00	100.00	600.00	40.00	41.00
S_{15}	1000.00	1510.00	270.00	150.00	220.00	8.00

Table 21:The removal ratios for the treatment plants (Case Study Three)

Process	Removal Ratio (%)				
	BOD	TSS	COD	NO_3^-	TDS
TP_1	0.00	0.00	99.00	0.00	0.00
TP_2	99.00	0.00	0.00	0.00	0.00
TP_3	0.00	0.00	0.00	0.00	99.00
TP_4	0.00	0.00	0.00	99.00	0.00
TP_5	0.00	99.00	0.00	0.00	0.00

Step 1:

Identify which pollutant is the main one for each treatment unit: for TP_1, the targeted pollutant is pollutant C; for TP_2, it is pollutant A; for TP_3, it is pollutant E; for TP_4, it is pollutant D; and for TP_5, it is pollutant B.

Step 2:

Determine the flow rate necessary in a given stream (i) to eliminate a specific pollutant (j). Equation (1) is used to compute the total lowest flow rates that each treatment unit must achieve in order to eliminate the contaminant from all streams, and these values are displayed in Table 22 and Table 23.

Table 22:The TP_1 and TP_2 flow rate values (Case Study Three).

TP_1		TP_2	
Flow rate (t/h)	**C**	**Flow rate (t/h)**	**A**
$F^1_{1,C}$	35.32	$F^2_{1,A}$	32.73
$F^1_{2,C}$	24.08	$F^2_{2,A}$	23.84
$F^1_{3,C}$	14.89	$F^2_{3,A}$	14.98
$F^1_{4,C}$	22.73	$F^2_{4,A}$	0
$F^1_{5,C}$	---	$F^2_{5,A}$	13.64
$F^1_{6,C}$	---	$F^2_{6,A}$	---
$F^1_{7,C}$	8.91	$F^2_{7,A}$	8.33
$F^1_{8,C}$	1.82	$F^2_{8,A}$	1.97
$F^1_{9,C}$	2.88	$F^2_{9,A}$	2.99
$F^1_{10,C}$	20.65	$F^2_{10,A}$	22.30
$F^1_{11,C}$	74.92	$F^2_{11,A}$	---
$F^1_{12,C}$	0.51	$F^2_{12,A}$	---
$F^1_{13,C}$	4.90	$F^2_{13,A}$	5.03
$F^1_{14,C}$	37.27	$F^2_{14,A}$	---
$F^1_{15,C}$	7.78	$F^2_{15,A}$	8
$\sum F^1_{T,C}$	256.66	$\sum F^2_{T,A}$	133.81

Table 23:The TP_3, TP_4, and TP_5 flow rate values (Case Study Three).

TP_3		TP_4		TP_5	
Flow rate(t/h)	**E**	**Flow rate (t/h)**	**D**	**Flow rate(t/h)**	**B**
$F^5_{1,E}$	31.17	$F^4_{1,D}$	---	$F^3_{1,B}$	29.09
$F^5_{2,E}$	23.98	$F^4_{2,D}$	---	$F^3_{2,B}$	23.94
$F^5_{3,E}$	14.49	$F^4_{3,D}$	14.14	$F^3_{3,B}$	---
$F^5_{4,E}$	24.96	$F^4_{4,D}$	25.17	$F^3_{4,B}$	0
$F^5_{5,E}$	17.92	$F^4_{5,D}$	17.82	$F^3_{5,B}$	17.11
$F^5_{6,E}$	34.31	$F^4_{6,D}$	33.59	$F^3_{6,B}$	35.05
$F^5_{7,E}$	7.79	$F^4_{7,D}$	9.05	$F^3_{7,B}$	0
$F^5_{8,E}$	1.99	$F^4_{8,D}$	1.35	$F^3_{8,B}$	1.01
$F^5_{9,E}$	2.89	$F^4_{9,D}$	2.65	$F^3_{9,B}$	2.94
$F^5_{10,E}$	22.83	$F^4_{10,D}$	---	$F^3_{10,B}$	22.37
$F^5_{11,E}$	87.47	$F^4_{11,D}$	85.99	$F^3_{11,B}$	89.14
$F^5_{12,E}$	0.91	$F^4_{12,D}$	0.99	$F^3_{12,B}$	---
$F^5_{13,E}$	3.37	$F^4_{13,D}$	---	$F^3_{13,B}$	4.97
$F^5_{14,E}$	31.06	$F^4_{14,D}$	40.72	$F^3_{14,B}$	41-
$F^5_{15,E}$	7.71	$F^4_{15,D}$	7.54	$F^3_{15,B}$	8.03
$\sum F^5_{T,E}$	312.85	$\sum F^4_{T,D}$	239.01	$\sum F^3_{T,B}$	192.65

Table 24: Determining the pinch stream for TP_2 to eliminate the pollutant A (Case Study Three).

Stream	F_i (t/h)	$C_{i,A}$(ppm)	$m_{i,A}$ (g/h)	$\sum m_{i,A}$(g/h)
S_{13}	5	2000	10000	10000
S_{15}	8	1000	8000	18000
S_9	3	900	2700	20700
S_3	15	900	13500	34200
S_2	24	600	14400	48600
S_8	2	370	740	49340
S_{10}	23	250	5750	55090
S_7	9	120	1080	56170
S_1	36	100	3600	59770
S_5	18	40	720	60490
S_4	25	10	250	60740
S_{12}	1	0	0	60740
S_6	35	0	0	60740
S_{14}	41	0	0	60740
S_{11}	89	0	0	60740
Sum	334		60740	

Step 3:
As shown in Tables 22, 23, the process sequence follows the order of TP_2, TP_5, TP_4, $TP_1$and TP_3prioritizing the process with the minimum flow rate to be carried out first.

Step 4:
Equation (2) is used to compute the minimal removal mass load for all pollutants using the figures in Tables 24, 25, 26, 27 and 28.

Table 25: Determining the pinch stream for TP_5 to eliminate the pollutant B (Case Study Three).

Stream	F_i (t/h)	$C_{i,B}$(ppm)	$m_{i,B}$ (g/h)	$\sum m_{i,B}$ (g/h)
S_{11}	89	1190	105910	105910
S_6	35	1100	38500	144410
S_{m1}	107.10	397.53	42575.46	186985.46
S_5	18	170	3060	190045.46
S_1	17.90	50	895	190940.46
S_4	25	10	250	191190.46
S_{14}	41	5	205	191395.46
S_{12}	1	0	0	191395.46
Sum	334		191395.46	

Table 26: Determining the pinch stream for TP_4 to eliminate the pollutant D (Case Study Three).

Stream	F_i (t/h)	$C_{i,D}$(ppm)	$m_{i,D}$ (g/h)	$\sum m_{i,D}$ (g/h)
S_4	25	3000	75000	75000
S_{12}	1	800	800	75800
S_{14}	41	600	24600	100400
S_5	0.53	500	265	100665
S_{m2}	248.57	233.15	57954.10	158619.10
S_1	17.90	0	0	158619.10
Sum	334		158619.10	

Table 27: Determining the pinch stream for TP_1 to eliminate the pollutant C (Case Study Three).

Stream	F_i (t/h)	$C_{i,C}$(ppm)	$m_{i,C}$ (g/h)	$\sum m_{i,C}$ (g/h)
S_1	17.90	350	6265	6265
S_{m2}	7.60	273.18	2076.17	8341.17
S_{m3}	308.50	234.84	72448.14	80789.31
sum	334		80789.31	

Table 28: Determining the pinch stream for TP_3 to eliminate the pollutant E (Case Study Three).

Stream	F_i (t/h)	$C_{i,E}$(ppm)	$m_{i,E}$ (g/h)	$\sum m_{i,E}$ (g/h)
S_{m3}	10.89	394.32	4294.14	4294.14
S_{m4}	323.11	376.67	121705.84	125999.98
sum	334		125999.98	

The smallest mass loads that need to be eliminated, considering the discharged contaminant concentration of 10 ppm, are computed using Equation (1) and the figures from Tables 24, 25, 26, 27 and 28.The results are as follows:

M_C^{rem} =77449.31 g/h, M_B^{rem} =188055.46 g/h, M_A^{rem} = 57400 g/h, M_E^{rem} =122659.98g/h,and M_D^{rem} =155279.10 g/h

Step 5:

Utilizing Equation (3), the mass load at TPk's entrance and the relevant pinch streams are computed and briefed in Table 29.

Table 29: Contaminant Types and Their Mass Loads at Treatment unit entrance and Pinch Stream (Case Study Three).

Contaminant	TP_k	M_{TP_k}	Pinch stream
A	2	57979.79	S_1
B	5	189955.01	S_5
C	1	78231.63	S_{m3}
D	4	156847.58	S_{m2}
E	3	123898.97	S_{m4}

Step 6:

The portions of the pinch stream that need to be treated and bypassed are computed using Equations (4) and (5), resulting in the following values: $F_{TP_{1,pt}} = 297.61$ t/h, $F_{TP_{1,pb}} = 10.89$ t/h, $F_{TP_{2,pt}} = 18.10$ t/h, $F_{TP_{2,pb}} = 17.90$ t/h, $F_{TP_{3,pt}} = 317.53$ t/h, $F_{TP_{3,pb}} = 5.58$ t/h, $F_{TP_{4,pt}} = 240.97$ t/h, $F_{TP_{4,pb}} = 7.60$ t/h, $F_{TP_{5,pt}} = 17.47$ t/h,and $F_{TP_{5,pb}} = 0.53$ t/h

Step 7:

The smallest treatment flow rates for each treatment facility are computed utilizing Equation (6). The results are as follows: $F_{TP_1} = 323.11 t/h$, $F_{TP2} = 107.10 t/h$, $F_{TP3} = 328.42 t/h$, $F_{TP4} = 308.50 h$, and $F_{TP5} = 248.57 t/h$,

Figure 4 The final proposed design network is based on the design steps outlined in this paper.

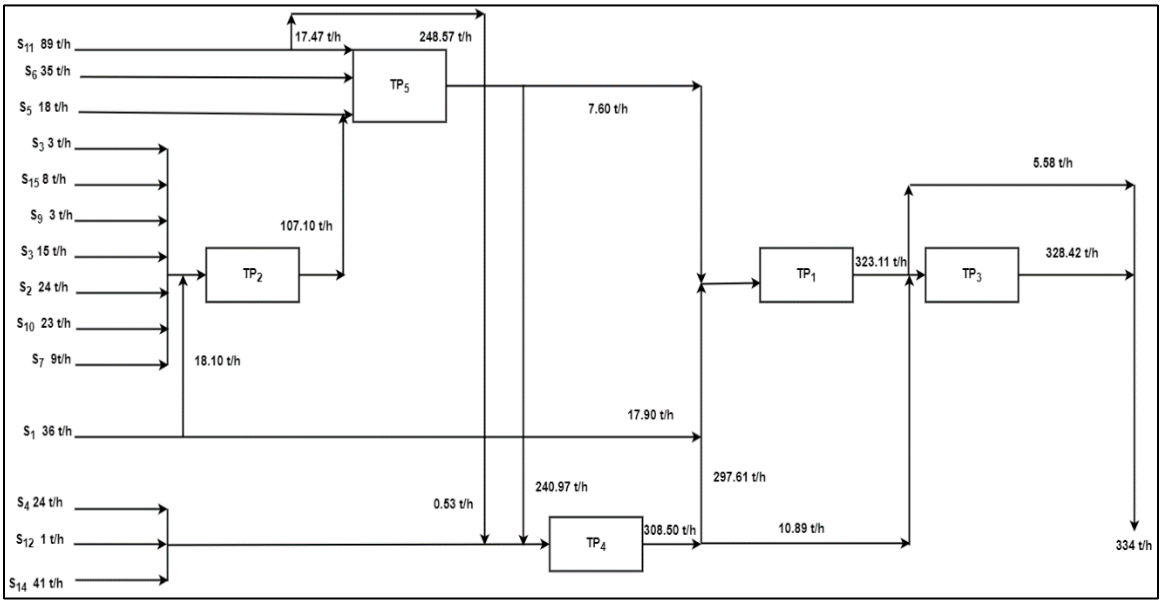

Figure 4. The final proposed design network (Case Study Three)

4. Results and Discussion

This paper primarily focuses on reducing the pollutant load discharged into the environment, whereas the literature emphasizes reducing the flow rate[4,10,11]. Wastewater treatment networks in this study are designed with an environmental limit of 10 ppm. It is assumed that each treatment unit is responsible for removing a single pollutant, with an additional focus on increasing removal ratios. In contrast, the literature typically designs wastewater treatment plants with an environmental limit of 100 ppm. In this work, three cases were studied, each differing in the number of streams requiring treatment as well as the number of treatment units. It is evident that as the number of streams increases, the mixing ratio of the streams also increases, leading to a higher total flow rate. Specifically, the total flow rate is 115.64 t/h, 278.47 t/h, and 1315.70 t/h for the first, second, and third cases, respectively. As shown in Tables 30, 31 and 32, the objective of this study has been achieved by discharging pollutants into the environment at the targeted values for Egypt Vision 2030.

Table 30: The final discharged concentration for all contaminants (Case Study One)

C_{env}^{dis} (ppm)			
F_T (t/h)	C_A	C_B	C_C
40	9.40	9.99	10

Table 31: The final discharged concentration for all contaminants (Case Study Two)

C_{env}^{dis} (ppm)						
F_T (t/h)	C_A	C_B	C_C	C_D	C_E	C_F
57	9.97	9.99	10	10	9.97	9.99

Table 32: The final discharged concentration for all contaminants (Case Study Three)

C_{env}^{dis} (ppm)					
F_T (t/h)	C_A	C_B	C_C	C_D	C_E
334	9.99	9.99	10	9.99	10

The comparison of Cases One, Two, and Three shows how pinch analysis and mass load balancing may be used effectively to optimize multi-contaminant wastewater treatment networks. In order to remove pollutants effectively with the least amount of treatment resources, this methodology connects flow and concentration data with environmental discharge restrictions. The sequencing of treatment units according to the overall needed flow rates—with the units with the lowest treatment flow demand being prioritized first—is a crucial tactic used in those situations. This method reduces overlapping treatment efforts throughout the network and enables a more effective distribution of stream loads. The flow contributions of all streams that require treatment for a given pollutant are first added up to determine the total flow needed by each treatment unit. A flow rate of zero means that no additional treatment is necessary because the stream's input concentration already satisfies the allowable discharge limit. If the computed flow rate is negative, on the other hand, it indicates that the stream not only doesn't need to be treated but also helps other streams in that unit by providing compensating capacity, which lessens their treatment burden.

The system in Case One handles three pollutants, A, B, and C, each of which is assigned to a specific treatment unit (TP3, TP2, and TP1, respectively). Treatment unit sequencing is done using a flow-based prioritization method, and table 4 shows that TP3 (for pollutant C) has the highest priority because it requires the least amount of flow (38.23 t h^{-1}), followed by TP2 (B) at 39.18 t h^{-1} and TP1 (A) at 39.44 t h^{-1}. By starting the treatment network with the most effective unit, this order maximizes the reduction of pollutants in the early stages. Which streams should be totally, partially, or bypassed is determined by comparing the incoming mass load of each treatment unit with the necessary pollutant removal.For example, TP3 concentrates on pollutant C, and table 5 shows that stream S2 is the pinch stream determined by the pinch analysis. Treatment accounts for 12.22 t h^{-1} of its total flow, while bypass accounts for 2.78 t h^{-1}. Similar optimization takes place in TP2, where S2 is partially treated (see table 6), and in TP1, where S2 is separated appropriately and becomes the pinch stream (see table 7). While reducing treatment volume, these flow modifications guarantee that the precise mass of the pollutant is eliminated. With its specialized treatment units and accurate pinch stream detection and split treatment techniques, Case One is an all-around straightforward system.

As opposed to Case Three, which has five pollutants and five treatment units, Case Two has six pollutants and six treatment units. Additional factors are taken into account when sequencing the treatment units because of this intricacy.According to table 11 and table 12, the sequencing of treatment units uses a flow-based prioritization approach, with TP6 (for pollutant F) receiving the highest priority because of its lowest required flow of 29.44 t h^{-1}, followed by TP2 (B) at 48.62 t h^{-1}, TP1 (A) at 53.79 t h^{-1}, TP3 (C) at 54.24 t h^{-1}, TP4 (D) at 55.34 t h^{-1}, and TP5 (E) at 56.44 t h^{-1} in Case Two.In Case Three, however, as indicated in Tables 22 and 23, TP2 (A) is likewise given priority at 133.81 t h^{-1}, followed by TP5 (B) at 192.65 t h^{-1}, TP4 (D) at 239.01 t h^{-1}, TP1 (C) at 256.66 t h^{-1}, and TP3 (E) at 312.85 t h^{-1}. Tables 24, 25, 27, and 28 demonstrate that the pinch stream for TP1, TP2, TP3, TP4, and TP5 is sm3, S1, Sm4, Sm2, and S5, respectively. Overall, Cases Two and Three illustrate more complicated systems with numerous pollutants and treatment units. To manage overlapping contaminant loads and attain compliance, efficient optimization depends on precise pinch stream identification, flow-based prioritization, and complex split treatment techniques.

5. Conclusions

In this paper, we achieved the objectives of the study by reducing the discharged pollutant concentration to 10 ppm, thereby reducing the pollutants' mass loads released into the environment. The analysis of removal mass loads for various contaminants reveals significant variations across the treatment plants and case studies. For Contaminant A, the lowest removal mass loads were 18,599.97 g/h, 29,370.36 g/h, and 57,400 g/h, achieved by TP1, TP1, and TP2 in Case One, Case Two, and Case Three, respectively. For Contaminant B, the lowest removal mass loads were 17,599.90 g/h, 16,640.03 g/h, and 188,055.46 g/h, removed by TP2, TP2, and TP5 in the same cases. Similarly, the lowest removal mass loads for Contaminant C were 12,100 g/h, 15,929.92 g/h, and 77,449.31 g/h, recorded by TP3, TP3, and TP1, respectively. For Contaminant D, the lowest removal mass loads were 15,630 g/h and 155,279.10 g/h, removed by TP4 in Case Two and Case Three, respectively. Contaminant E exhibited the lowest removal mass loads of 42,179.60 g/h and 122,659.98 g/h, achieved by TP6 and TP3 in Case Two and Case Three, respectively. In the end, the lowest removal mass load for pollutant F was 42,179.60 g/h, eliminated by TP5 in Case Two.
The removal ratio for the treatment plants (TP) was set at 99%, and the maximum allowable environmental limit concentration was set at 10 ppm. The results indicate that:

1) In case study one, the flow rates of TP1, TP2, and TP3 are 39.53 t/h, 38.89 t/h, and 37.22 t/h, respectively.
2) In case study two, the flow rates of TP1, TP2, TP3, TP4, TP5, and TP6 are 56.32 t/h, 54.64 t/h, 55.15 t/h, 55.55 t/h, 56.81 t/h, and 26.64 t/h, respectively.
3) In case study three, the flow rates of TP1, TP2, TP3, TP4, TP5, and are 323.11 t/h, 107.10 t/h, 328.67 t/h, 308.50 t/h, 308.50 t/h, and 248.57 t/h, respectively. Designing wastewater treatment systems to reach discharge limitations below legal maximums is a proactive and long-term strategy that provides major environmental, social, and economic benefits. This technique promotes long-term environmental sustainability by lowering pollutants, conserving ecosystems, and avoiding health hazards. Furthermore, it aligns with Egypt's Vision 2030, prioritising sustainable water management, environmental preservation, and efficient resource exploitation.

This methodical approach emphasizes how crucial it is to prioritize treatments according to flow rate values and use pinch analysis to allocate streams as efficiently as possible. through the identification of vital streams and the balancing of bypassed and treated portions. The analysis offers a solid framework for industrial applications needing effective pollutant removal, notwithstanding its assumption of steady-state circumstances and rigorous adherence to the 10 ppm limit. The approach used in this work is both simple and technically focused. Its computational effort remains largely unaffected by the number of streams, pollutants, or treatment units.

Overall, the three scenarios demonstrate how well pinch analysis and mass load balancing work together to create treatment networks that are both economical and environmentally responsible. Case one successfully illustrates the method's fundamental use with its more straightforward design and specialized treatment units. Cases Two and Three, on the other hand, demonstrate its versatility and effectiveness in more intricate systems that include several contaminants, multipurpose treatment units, and interstream flow correction. By incorporating zero and negative flow rates into the sequencing method, the flexibility of stream allocation is greatly increased, allowing for more intelligent network design that minimizes treatment redundancy and maximizes resource utilization.

6. Funding sources

This research received no external funding.

7. Conflicts of interest

There are no conflicts to declare.

8. Nomenclature

$C_{i,j}^{in}$ /ppm : stream i's inlet concentration of contaminant j..
$C_{env,j}^{lim}$ /ppm: Environmentally acceptable limit of contaminant j in S_i.
C_{env}^{dis} /ppm : environmental discharged concentration.
$C_{i,j}$ /ppm : concentration of contaminant j in S_i.
$C_{p,j}$: Concentration of pollutant j at stream point.
$F_{i,j}^{k}$: Process k's flow rate to eliminate contaminant j in stream i

$F_{T,j}^{k}$: Process k's minimal total flow rate to eliminate contaminant j in all streams.
f_i : stream i's flow rate.
$f_{TPk,pt}$: Sp flow rate required treatment by TP_k..
$f_{TPk,pb}$: Sp flow rate does not require TP_k treatment..
F_{TPk} : the minimal treatment flow rate of treatment unit K.
M_j^{rem} : The smallest mass load of pollutant j had to be removed.
$M_{Tpk,j}$: Pollutant load j at TP_k's entrance
$m_{i,j}$: mass load of contaminant j in S_i.
M_{Si} / t/h : mass load at S_i.
RR / % : removal ratio.
S_i : stream *i*.
P : process
S_m : merged stream.
S_p : pinch stream.
S_{pb} : A part of the pinch stream is being bypassed.
S_p : stream point.
TP_k : treatment plant *k*.

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