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Optimization of Dynamically Adjusting Segregation Strategies in Wastewater Treatment Plants

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Wastewater treatment is critical for preserving the limited global supply of clean water but remains highly energy-intensive, with growing demand driving increased fossil fuel consumption in WWTPs. This study examines the integration of a dynamic segregation system that adjusts in real-time to fluctuations in water quality and flow. By minimizing unnecessary treatments, the system improves efficiency and reduces energy use. Literature shows that water quality variability is common, and periodic decision-making adjustments enhance treatment effectiveness. As regulatory penalties and inefficiencies grow more costly, dynamic segregation presents a viable long-term solution for sustainable and cost-effective wastewater management.

1. Introduction

Only 0.5 % of Earth’s water is readily usable by humans (Baker et al., 2016). Contamination from urban, agricultural, and industrial activities has further strained this limited supply, making wastewater treatment essential for environmental protection and water security. Conventional treatment processes, however, are highly energy intensive. In 2015, China’s activated sludge systems alone consumed over 25.15 B kWh (Zhang et al., 2020). More broadly, wastewater treatment accounts for about 35 % of municipal energy consumption (Masłoń, 2017) and contributes over 50 % of greenhouse gas emissions within the water sector (Nakkasunchi, 2020). These figures emphasize the urgency of pursuing more energy-efficient treatment strategies.

Wastewater segregation has emerged as a promising approach, reducing energy use by routing influent based on contaminant profiles and avoiding overtreatment (Ranade et al., 2014). Other energy recovery options, such as microalgae cultivation, have also been explored, although their effectiveness depends on environmental variables like natural light (Singh et al., 2024). Water quality can also fluctuate due to seasonal changes or the presence of emerging contaminants like antibiotics and algae (Caligan et al., 2021), affecting removal efficiency and treatment reliability (Guo et al., 2025). These challenges are particularly pronounced with the rise of decentralized treatment systems (Leigh and Lee, 2019), where variability has a larger operational impact (Van De Walle et al., 2022).

Real-time monitoring tools, such as IoT sensors, can provide continuous influent quality data for operational decision-making (Goncalves et al., 2020). For instance, AI-based control systems have been shown to improve treatment efficiency by adjusting oxidant dosing in response to changing influent conditions (Pham et al., 2022). Liew et al. (2014) extended water pinch to multiperiod planning but retained a fixed network, used a single aggregated water quality parameter, and focused solely on freshwater minimization. Other works, such as Caligan et al. (2022), also prioritize water use minimization without explicitly modeling operational trade-offs between different segregation strategies. This study addresses these gaps by developing a multiperiod model tailored to segregation-based WWTPs that integrates treatment-stream-specific efficiencies, energy use, freshwater intake, and segregation costs into a unified cost-minimization framework. Unlike multiperiod water pinch, the proposed method allows routing to change each period in response to contaminant profiles and cost priorities and directly compares fixed versus dynamic segregation within the same system to quantify the operational and economic benefits of flexibility.

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2. System Definition

The optimization model incorporates operational, energy, and environmental costs, including freshwater usage and release. Building on Sa'ad et al. (2022) and Alfaisal (2024), it enables dynamic segregation of wastewater from multiple sources based on time-varying flows and contaminant levels, routing them to treatment streams with different removal efficiencies. An aggregate quality level is assumed for the treated water, serving as the basis for performance comparisons (San Juan et al., 2020). Freshwater is added as needed to meet volume and dilution requirements. The model adapts allocations over time to respond to quality fluctuations, subject to contaminant limits, treatment capacities, and mass balance constraints.

3. Model Formulation

3.1 Assumptions

In the dynamic segregation system, daily water flow and quality are segmented across multiple time periods rather than averaged over the entire day. All incoming wastewater is assumed to undergo treatment, and any treated volume exceeding the demand is discarded from the system. Freshwater, when introduced, is assumed to be free of contaminants.

3.2 Objective Function and Cost Components

The objective function in Eq(1) minimizes total treatment and water handling costs, including the cost of introducing and discharging water. Energy costs in Eq(2) depend on the segregation strategy and treatment chosen. Introduction and discharge costs are computed per liter, as shown in Eq(3) and Eq(4).

$$min\ Z = EC + WC + XC \tag{1}$$

$$EC = (EDyn \cdot X + \Sigma_t\, ETr_t) \cdot EP \tag{2}$$

$$WC = \Sigma_t\, FW_t \cdot WP \tag{3}$$

$$XC = \Sigma_t\, XW_t \cdot XP \tag{4}$$

3.3 Water Segregation

Wastewater from each source is routed to specific treatment streams. Eq(5) ensures source allocations match total inflow. Eq(6) and Eq(7) compute total water and contaminant mass per stream, while Eq(8) sets a limit on stream capacity. If fixed allocation is selected, Eq(9) and Eq(10) lock percentage distributions to prevent variation over time.

$$\Sigma_p\, Q_{ipt} = 1,\ \forall i, t \tag{5}$$

$$W_{pt} = \Sigma_i\, Q_{ipt}\, W_{it},\ \forall p, t \tag{6}$$

$$C_{pkt} = \Sigma_i\, Q_{ipt}\, C_{ikt},\ \forall p, k, t \tag{7}$$

$$W_{pt} + \Sigma_k\, C_{pkt} \leq Wmax_p,\ \forall p, t \tag{8}$$

$$Q_{ipt} \geq Qfix_{ip} - X,\ \forall i, p, t \tag{9}$$

$$Q_{ipt} \leq Qfix_{ip} + X,\ \forall i, p, t \tag{10}$$

3.4 Water Treatment

Wastewater that enters treatment undergoes a process where a given percentage of contaminant content is removed from a given stream, based on the removal efficiency, given in Eq(11). Eq(12) computes the energy consumption at any given period by multiplying the energy consumption with unit flow for each stream, summing them to get the total energy consumption.

$$Cout_{pkt} = C_{pkt}\,(1 - R_{pk}),\ \forall p, k, t \tag{11}$$

$$ETr_t = \Sigma_p\, ((W_{pt} + \Sigma_k\, C_{pkt}) \cdot ECons_p) \tag{12}$$

3.5 Water Distribution

Treated water is then aggregated, summing up the water and contaminant content from all streams, alongside introduced freshwater. Safety standards for contaminants are depicted in Eq(15), while tank capacity is listed in Eq(16). Lastly, water that is not used to satisfy demand is then released.

$$WD_t = \Sigma_p W_{pt} + FW_t, \ \forall t \quad (13)$$

$$CD_{kt} = \Sigma_p C_{pkt}, \ \forall k, t \quad (14)$$

$$CD_{kt} \leq ConcLimit_k \cdot (WD_t + \Sigma_k CD_{kt}), \ \forall k, t \quad (15)$$

$$WD_t + \Sigma_k CD_{kt} \leq CAP, \ \forall t \quad (16)$$

$$XW_t = WD_t + \Sigma_k CD_{kt} - Dem_t, \ \forall t \quad (17)$$

4. Illustrative Case Study

This case study examines three wastewater sources, each containing varying amounts of three contaminant types that fluctuate over 24 periods representing the hours in a day. The model can be adapted for other practical scenarios by adjusting the period length, for example, using 30 periods to represent daily variations over a month, or subdividing each hour into finer intervals for more dynamic, high-resolution adjustments. Figure 1 illustrates the general level of water flow from each source. For each source, one contaminant was selected to have a higher mass flow rate, while the other contaminants are to have a similar lower mass flow rate.

Likewise, three treatment streams (collectors) are available, each with varying removal efficiencies across the three contaminant types. The cost to treat 1 Liter of wastewater also differs per stream, and these values are summarized in Table 1.

Figure 2 shows that freshwater is added only when needed to meet volume requirements, due to its associated cost. Treated water consistently meets quality standards, indicating that dilution is unnecessary. This confirms that treatment streams alone are sufficient for contaminant removal, and freshwater is introduced solely to meet demand.

Figure 3 shows the allocation of wastewater from each source to different treatment streams over time. Two key factors drive these shifts: fluctuations in source water flow and changes in demand. During periods of lower demand, sources are primarily routed to the streams that are most effective at removing their dominant contaminants. As demand increases and freshwater supplementation becomes necessary, allocation shifts toward streams with the lowest treatment cost per L, prioritizing volume over efficiency. When demand tapers off, the system gradually returns to prioritizing contaminant-specific removal efficiency.

Table 1: Removal Efficiency and Cost per L of Treatment Streams

Efficiency	Contaminant 1	Contaminant 2	Contaminant 3	Cost per L
Stream 1	0.95	0.70	0.70	0.034
Stream 2	0.70	0.95	0.70	0.017
Stream 3	0.70	0.70	0.95	0.0255

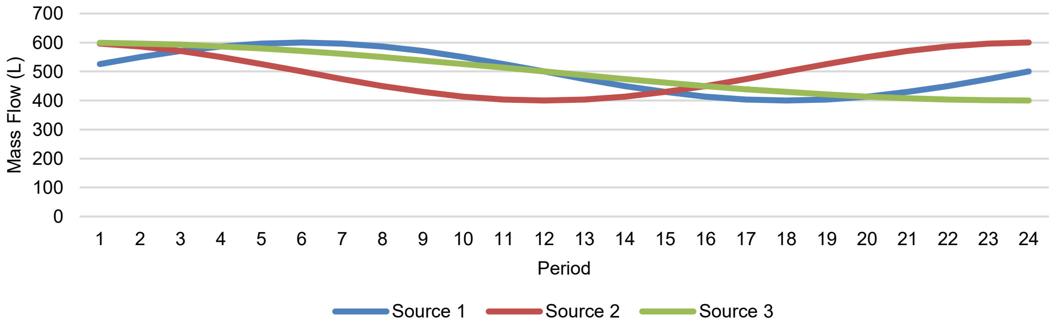

Figure 1: Water Flow in L from Sources 1 to 3 over 24 periods

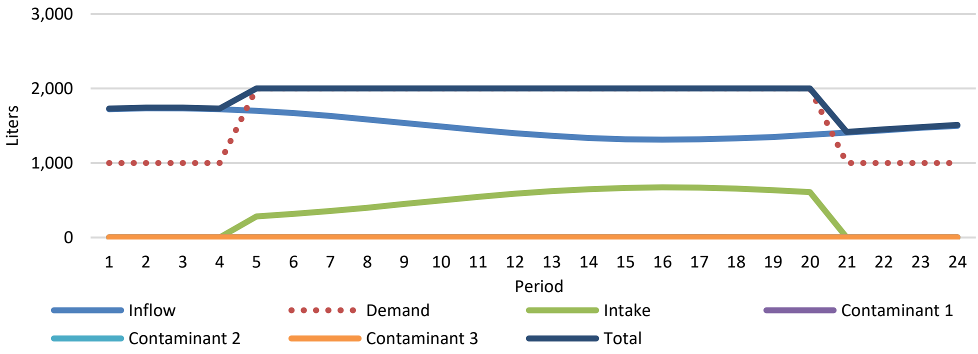

Figure 2: Water Intake in L per period

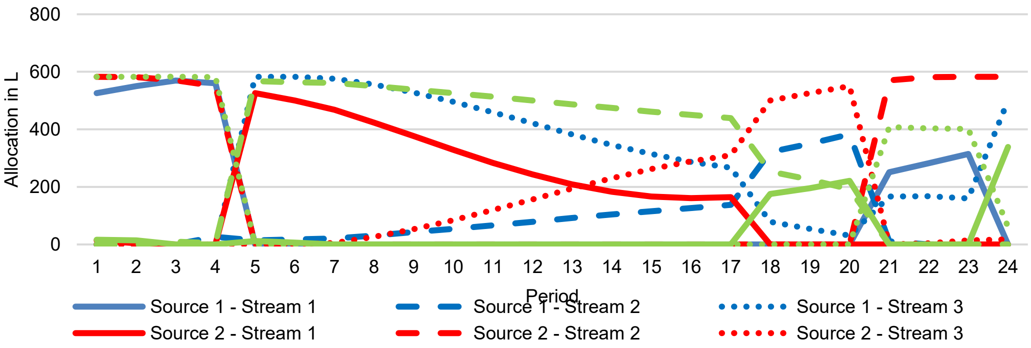

Figure 3: Allocation of Wastewater from Sources to Treatment Streams in L

The proposed dynamic system yields an energy cost of $ 899.94, freshwater costs of $ 8,622.80, and a water release cost of $ 48.08, totalling $ 9,570.82. This will be utilized as the basis for comparing other scenarios or decisions that would affect the system.

5. Scenario Analysis

5.1 Forced Fixed Segregation

Standard optimization models, such as Saad et al. (2022), typically assume fixed segregation infrastructure. In contrast, this study compares fixed and dynamic systems, with cost differences detailed in Table 2, including the percentage increase associated with fixed segregation. The results highlight the potential of dynamic systems to achieve meaningful operational cost reductions as seen in small optimizations that can have a significant impact given the high cost of developing and maintaining WWTPs.

Table 2: Cost Comparison between Dynamic and Fixed Segregation Systems

Scenario	Energy Cost	Freshwater Cost	Water Release Cost	Total Cost
Dynamic	$ 899.94	$ 8,622.80	$ 48.08	$ 9,570.82
Fixed	$ 911.28	$ 8,629.34	$ 48.36	$ 9,588.98
% Increase	1.26 %	0.07 %	0.58 %	0.02 %

5.2 Sustainability and Reduced Water Usage

To conserve limited water resources, reuse strategies are being explored. Jivani et al. (2025) propose using slightly contaminated water for industrial processes to reduce freshwater demand. However, with contaminant discharge unchanged, reduced flow (20 % lower in all periods) leads to higher concentrations. As shown in Table 3, this raises freshwater intake costs but lowers energy and treatment costs. While this approach offers potential long-term savings, especially since energy can potentially make up around 40 % of WWTP costs (Saghafi et al., 2016), it may increase treatment difficulty due to more concentrated waste.

As shown in Figure 4, rising contaminant concentrations require the addition of freshwater to dilute the effluent to acceptable levels. This results in a total fluid volume that exceeds actual demand, illustrating a trade-off between contamination control and resource efficiency. In such cases, introducing freshwater is often more cost-effective than applying stronger, more expensive treatment methods (Nemet et al., 2021).

Table 3: Cost Comparison between Original and Reduced Water Flow

Water Flow	Energy Cost	Freshwater Cost	Water Release Cost	Total Cost
Original	$ 899.94	$ 8,622.80	$ 48.08	$ 9,570.82
20 % Reduction	$ 664.30	$ 13,252.80	$ 22.63	$ 13,939.73

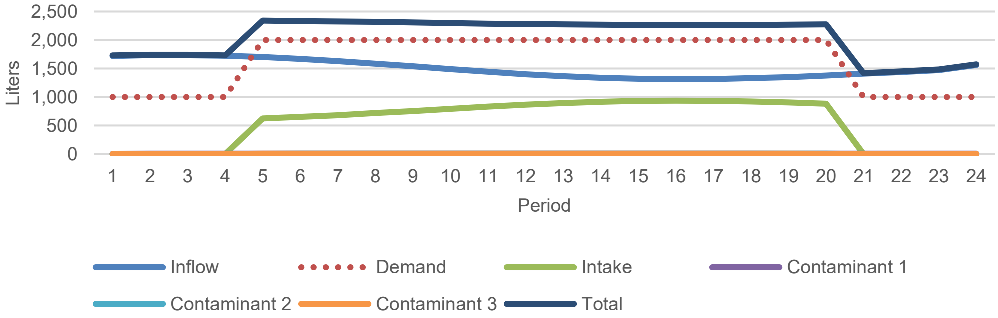

Figure 4: Freshwater intake patterns for reduced water flow rate, in L per period

Comparing the costs to the use of a fixed segregation system as seen in Table 4, a 1 % increase is observed for energy and water release costs, while the costs of introducing freshwater remain unchanged.

Table 4: Cost Comparison between Dynamic and Fixed Segregation Systems

Scenario	Energy Cost	Freshwater Cost	Water Release Cost	Total Cost
Dynamic	$ 664.30	$ 13,252.80	$ 22.63	$ 13,939.73
Fixed	$ 673.37	$ 13,252.80	$ 22.90	$ 13,949.06
% Increase	1.37 %	0.00 %	1.19 %	0.07 %

6. Conclusions

This study presents an optimization model for wastewater treatment plants that incorporates IoT-enabled dynamic segregation to enhance blue energy recovery. Unlike fixed systems, dynamic segregation offers greater flexibility and cost efficiency by adapting to fluctuations in wastewater quality and flow. By directing wastewater to the most suitable treatment streams, the system reduces energy use and improves contaminant removal, especially valuable in settings with high pollution levels or strict environmental regulations. Although IoT integration requires higher upfront investment, long-term savings make it economically viable for industrial and agricultural zones.

Future research could address limitations related to contaminant interactions, which may hinder treatment or cause adverse chemical reactions. Exploring the integration of multiple time-sensitive energy recovery methods such as algae biofuel and employing advanced tools such as nonlinear programming or system dynamics modeling may further improve system performance under variable conditions.

Nomenclature

Z – total cost, $
EC – total energy costs, $
WC– total freshwater costs, $
XC– total water release costs, $
EP – cost per unit energy, $/kWh
WP – cost per unit of freshwater, $/L
XP – cost per released freshwater, $/L
$EDyn$ – energy used in dynamic segregation, kWh
ETr_t – treatment energy per period, $
X – utilization of fixed or dynamic segregation, binary
FW_t – introduced freshwater, L
XW_t – released freshwater, L
Q_{ipt} – % allocation between sources and streams, -
W_{pt} – water content before treatment, L
C_{pkt} – contaminant content before treatment, L
$Wmax_p$ – maximum flow rate per period, L

$Qfix_{ip}$ – fixed value for allocation, -
$Cout_{pkt}$ – contaminant content after treatment, L
R_{pk} – contaminant removal efficiency, -
$ECons_p$ – energy consumption in treatment, kWh/L
WD_t – water content in distribution pool, L
CD_{kt} – contaminant content in distribution pool, L
$ConcLimit_k$ – maximum concentration of contaminant, -
Dem_t – water demand, L

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