



Seasonal Dynamics of Raw Water Quality and Pollution Load in the Sepaku River: Implications for Treatment Costs in Nusantara, Indonesia's New Capital

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<https://doi.org/10.18280/ij dne.210109>

ABSTRACT

Received: 14 July 2025

Revised: 29 August 2025

Accepted: 30 September 2025

Available online: 31 January 2026

Keywords:

raw water quality, pollution index, treatment cost, seasonal variability, Nusantara

The relocation of Indonesia's New Capital City (IKN) creates new challenges in ensuring sustainable and affordable drinking water provision. This study evaluates seasonal variation in raw water quality and pollution load along the Sepaku River, the primary source for IKN. Thirteen sampling stations were monitored during dry (February 2024) and rainy (December 2024) seasons, and parameters were assessed using the Pollution Index (PI) and Pollution Load (PL) methods. Results indicate that water quality ranged from lightly to moderately polluted (PI: 1.2–9.8), with pollutant loads increasing sharply during the rainy season. Peak concentrations were recorded for total suspended solids (TSS) at S3 (3.29×10^6 mg/L), biochemical oxygen demand (BOD) at S5 (1.88×10^5 mg/L), and nitrate at S7 (1.27×10^5 mg/L). Flow 2 (Sepaku Semoi Dam) showed more stable quality than Flow 1 (Sepaku River), suggesting a more reliable intake option. Cost simulations demonstrate that chemical treatment costs average IDR 404/m³, with total production costs estimated at IDR 3,313.5/m³. Seasonal deterioration in raw water quality may increase annual costs by up to IDR 19 billion. These findings highlight that upstream pollution control, catchment management, and adaptive treatment technologies are critical to maintaining affordability and resilience in Nusantara's drinking water system.

1. INTRODUCTION

The sequence of our studies on drinking water for Indonesia's New Capital City (IKN) can be mapped under the conceptual framework of Input–Throughput–Output of the drinking water supply system (Figure 1) [1]. The framework of the drinking water supply system employs a systemic lens to understand water provision, linking upstream raw water sources (input), technological and institutional processes (throughput), and service delivery to communities (output).

At the input stage, studies examined raw water availability and long-term sustainability forecasting [2], environmental carrying capacity based on water balance, and the quality of raw water. At the throughput stage, research addressed technological, infrastructural, and sustainable distribution design integrating hydraulic efficiency and cost considerations [2, 3] and the comparative evaluation of Multi-Utility Tunnel versus conventional methods for IKN infrastructure. At the

output stage, the framework emphasizes drinkable water provision coverage as a stochastic outcome, highly dependent on (1) competitive tariff setting, (2) subsidy mechanisms, (3) demand rate, and (4) the drinking water condition in terms of quality, quantity, and continuity. While institutional and governance challenges were analysed through a comparative study of Jakarta and Kuala Lumpur, culminating in a proposed institutional model for IKN's piped water system [4].

The trajectory research from 2023 to 2025 demonstrates a coherent and evolving research sequence, progressively covering input–throughput–output dimensions of sustainable water provision for IKN. Collectively, this sequence demonstrates a holistic trajectory from assessing raw water sources to designing efficient distribution systems and ultimately to ensuring equitable and sustainable service delivery. The integration of hydrological, engineering, and financial perspectives strengthens the applicability of the findings to real-world policy and infrastructure planning.

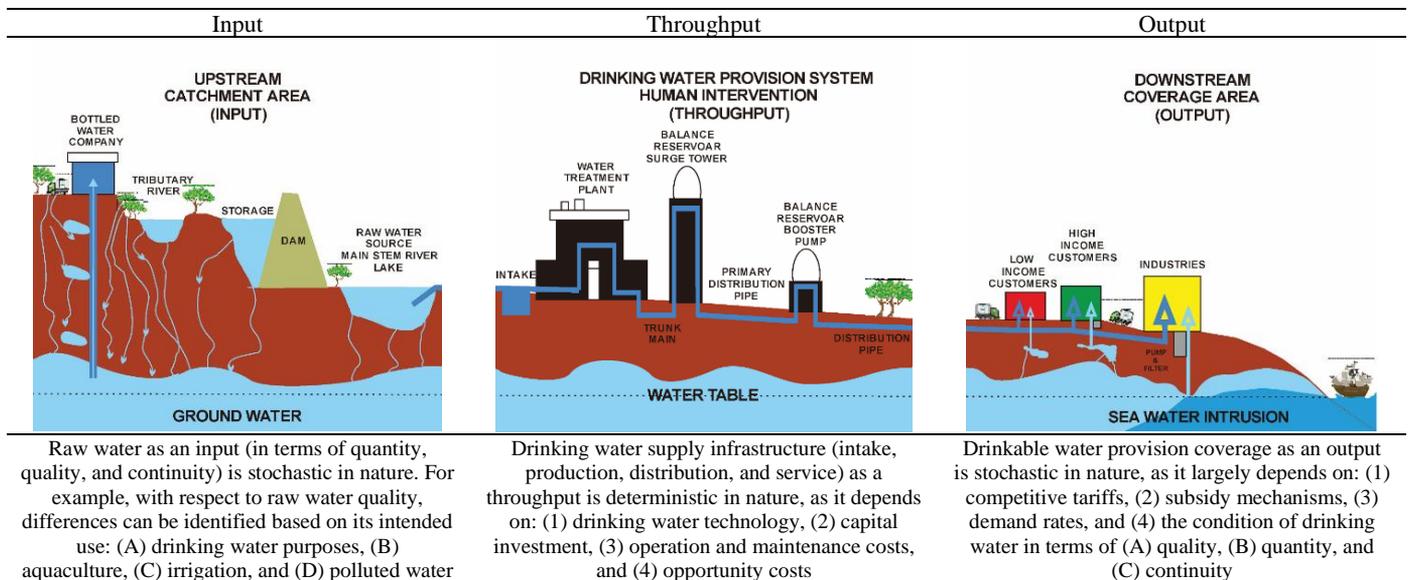


Figure 1. Input–Throughput–Output of drinking water supply system
Source: Studies [1, 4, 5]

A critical knowledge gap remains regarding variation in raw water quality and pollution load, which affects the overall cost and sustainability of drinking water provision. The primary research question guiding this study is: How does variation in raw water quality and pollution load along the Sepaku River influence water treatment complexity and production costs, and what integrated management strategies are required to ensure affordable and sustainable drinking water provision for Nusantara?

The objectives of this study are fourfold: (1) to evaluate the variation of raw water quality status of IKN water sources using physical, chemical, and biological parameters; (2) to quantify the pollution load dynamics between dry and rainy seasons; (3) to estimate the treatment costs associated with varying pollution levels, including the role of chemical consumption; and (4) to analyse the implications for sustainable water provision coverage, recognizing its stochastic dependence on tariff, subsidies, demand, and water condition (quality, quantity, continuity).

By addressing these objectives, this research extends the input–throughput–output trajectory and provides actionable insights for designing cost-effective and resilient water supply strategies in IKN, with broader implications for urban water management in tropical regions.

2. METHODS

2.1 Location of the study

The research was conducted in IKN. The IKN region encompasses two regencies: Penajam Paser Utara Regency, covering Penajam and Sepaku sub-districts, and Kutai Kartanegara Regency, covering Loa Kulu, Loa Janan, Muara Jawa, and Samboja sub-districts. The IKN area is located north of Balikpapan City and south of Samarinda City, encompassing a land area of approximately 256,142 hectares and a marine area of approximately 68,189 hectares (see Figure 2).

With the projected population of Nusantara expected to reach 1,542,000 by 2035, the drinking water supply scenario from 2025 to 2035 will rely on two primary raw water sources (see Figure 2): (1) the Sepaku Semoi Dam (Location A) and

(2) the Sepaku River Intake (Location B) (Figure 3) [1]. From Location A, approximately 2,500 L/s of raw water will be extracted, of which 350 L/s will be conveyed to Location C. From Location B, about 3,000 L/s will be extracted, treated, and distributed, including 900 L/s delivered to Location C. In total, the planned supply capacity of around 5,500 L/s is designed to support the long-term demand of the new capital. This allocation not only secures the immediate needs of the early development phase but also provides flexibility for future growth, ensuring that the raw water system remains resilient to demographic expansion and seasonal variability.

However, the reliability of this supply depends not only on capacity but also on raw water quality and variability. The Semoi Dam offers more stable flows, while the Sepaku River intake is vulnerable to pollution and fluctuations, requiring adaptive management to balance treatment needs and costs. These dynamics underscore the necessity of integrating water quality monitoring with long-term infrastructure planning.

2.2 Data collection

Table 1. Geographic coordinates of sampling stations (WGS-84)

Station Code	Latitude (S)	Longitude (E)
T1	0°53'53" S	116°51'36" E
T2	0°54'24" S	116°50'50" E
T3	0°54'33" S	116°50'28" E
T4	0°54'57" S	116°50'14" E
S1	0°53'16" S	116°45'50" E
S2	0°53'42" S	116°46'21" E
S3	0°53'52" S	116°46'14" E
S4	0°53'57" S	116°46'12" E
S5	0°54'12" S	116°46'11" E
S6	0°54'25" S	116°46'10" E
S7	0°54'44" S	116°46'10" E
S8	0°55'51" S	116°45'40" E
S9	0°57'07" S	116°45'16" E

Sampling locations were determined using a purposive sampling approach, targeting projected raw water sources for IKN at the Sepaku Semoi Dam (Location A) and the Sepaku River intake (Location B) (see Figure 4). Field campaigns were conducted twice to capture seasonal variability: 9–23

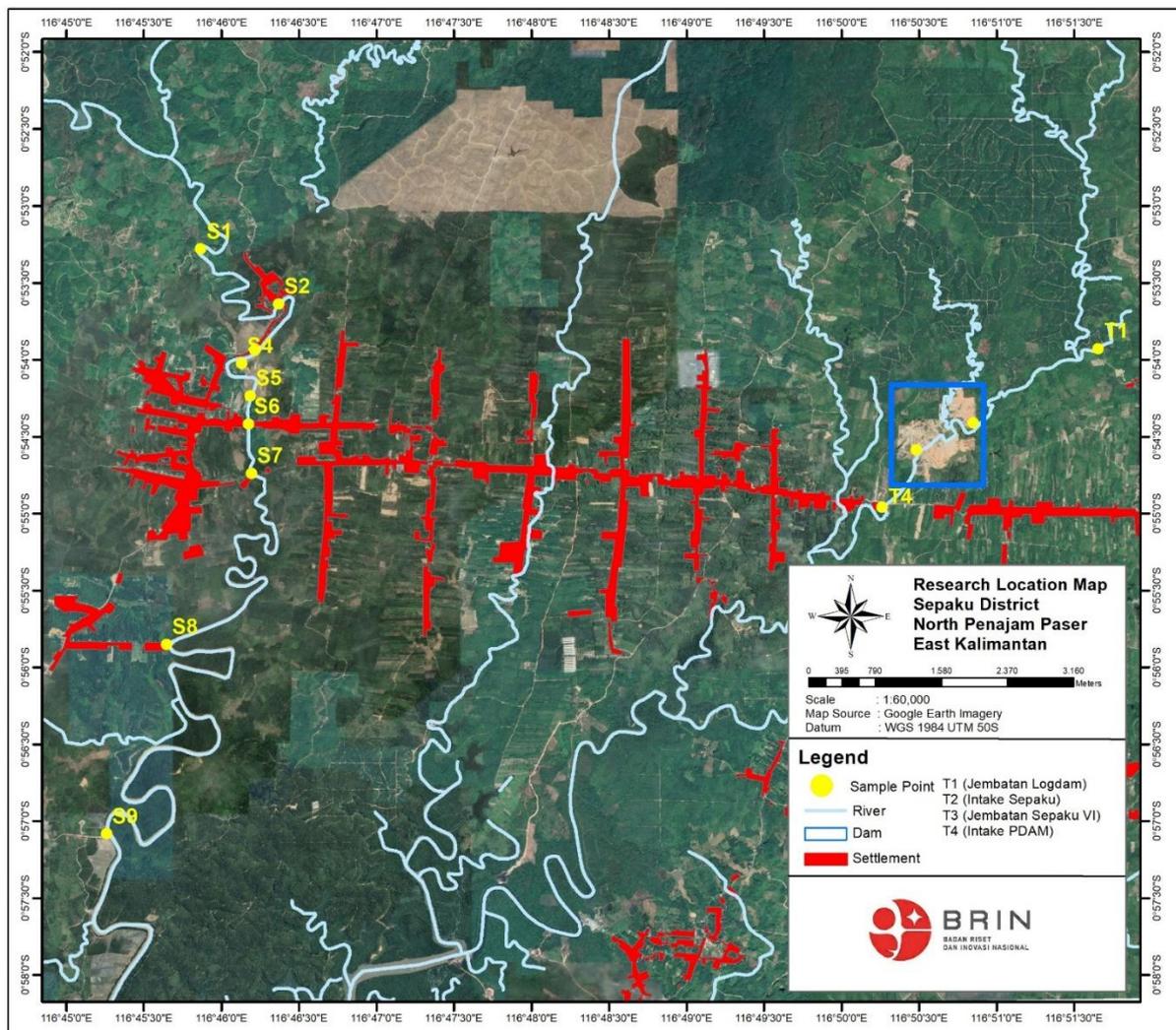


Figure 4. Water sampling location

Table 2. Sampling schedule

No.	Sampling Period	Dominant Season in East Kalimantan	Key Hydrological Condition	Relevance for the Study
1	9–23 February 2024	End of Rainy Season / Transition to Dry	River discharge is relatively lower; water quality is more stable (baseline)	Captures baseline water quality and pollution status under minimal runoff influence
2	2–6 December 2024	Peak of Rainy Season	High discharge, increased surface runoff, and elevated pollutant load	Represents extreme pollution conditions, critical for pollutant load analysis and treatment cost estimation

Water samples must be analyzed promptly to maintain accurate results. Chemical parameters such as pH, dissolved oxygen, BOD, and metal concentrations can change through oxidation, gas loss, or reactions with the container. Biological conditions may also shift as microorganisms grow or die, affecting coliform counts, nitrates, and other microbiological indicators. In addition, suspended solids can settle or react, altering the sample’s composition. Immediate analysis ensures that the measurements reflect the water’s true field conditions rather than changes that occur during storage. Therefore, water quality analysis in this study was conducted at the Environmental Laboratory of the Environmental Agency (DLH) of Kutai Kartanegara Regency, an accredited testing laboratory. Water quality analysis was carried out separately

for physical, chemical, and biological parameters in accordance with the APHA (2017) Standard Methods for the Examination of Water and Wastewater [6, 7], and was carried out in accordance with several Indonesian National Standards (SNI), including SNI 6989.59:2008 for Total Dissolved Solids (TDS), SNI 6989.3:2019 for Total Suspended Solids (TSS), SNI 6989.72:2009 for Biochemical Oxygen Demand (BOD), SNI 6989.2:2019 for Chemical Oxygen Demand (COD), SNI 6989.57:2008 for pH, and SNI 6774:2008 for maximum biological content in drinking water. The regulatory framework also refers to Minister of Health Regulation No. 2/2023 on Environmental Health and Minister of Environment and Forestry Regulation No. 27/2021 on Environmental Quality Index (see Table 3).

Table 3. Regulation to comply with and parameter sampling schedule

No.	Parameter	Regulation / Standard	Issuing Authority	Standard Value (Threshold)
1	Temperature (T)	Regulation of the Minister of Health No. 2/2023 on the Implementation of Government Regulation No. 66/2014 concerning Environmental Health	Ministry of Health of The Republic of Indonesia	26.3–33.1°C (± 3°C of ambient air temperature)
2	Total Dissolved Solids (TDS)	Government Regulation No. 22/2021 on the Implementation of Environmental Protection and Management	Government of Indonesia	≤ 1000 mg/L
3	Total Suspended Solids (TSS)	Government Regulation No. 22/2021	Government of Indonesia	≤ 40 mg/L
4	Colour (C)	Government Regulation No. 22/2021	Government of Indonesia	≤ 15 TCU
5	Salinity (S)	Government Regulation No. 22/2021	Government of Indonesia	≤ 6‰
6	Potential of Hydrogen (acidity/alkalinity) (pH)	Government Regulation No. 22/2021	Government of Indonesia	6–9
7	Biochemical Oxygen Demand (BOD)	Government Regulation No. 22/2021	Government of Indonesia	≤ 2 mg/L
8	Chemical Oxygen Demand (COD)	Government Regulation No. 22/2021	Government of Indonesia	≤ 10 mg/L
9	Nitrate (NO ₃)	Government Regulation No. 22/2021	Government of Indonesia	≤ 10 mg/L
10	Total Coliform (TC)	1) Government Regulation No. 22/2021 2) Minister of Health Regulation No. 2/2023	Indonesia; Ministry of Health of The Republic of Indonesia	≤ 1000 MPN/100 mL

2.3 Data analysis

At each sampling station, a comprehensive suite of physical, chemical, and biological parameters was measured. The physical parameters included temperature, TDS, TSS, and colour. The chemical parameters consisted of salinity, pH, nitrate (NO₃⁻), BOD, and COD, while biological quality was assessed through total coliform counts. For each parameter, the measured concentrations (C_i) were compared with Indonesian water-quality standards (L_{ij}) to evaluate compliance and potential risks to the proposed raw-water supply. Geographic coordinates of all sampling stations were recorded using GPS to allow spatial analysis and reproducibility for future monitoring.

To ensure scientific rigor and compliance with national standards, these parameters were evaluated against the official Indonesian regulatory framework. The regulations define threshold values and methodologies for interpreting physical, chemical, and biological indicators, thereby enabling the classification of raw water status and pollution load. Table 2 summarizes the key regulations, associated standard values, and the institutional authorities governing each parameter analysed in this study.

The integration of these regulatory standards ensures that the assessment of raw water quality in this study is not only based on robust scientific procedures but also aligned with Indonesia’s legal and institutional framework for water resource management, providing valuable input for decision-making [5]. Moreover, by aligning the analysis with nationally recognized thresholds, the findings gain credibility, remain comparable with other studies across the country, and directly support policy relevance. This regulatory grounding is essential for interpreting subsequent analyses, particularly the determination of water quality status using the pollutant index (PI) (Section 2.3.1) and the estimation of pollution load dynamics (Section 2.3.2).

2.3.1 Water pollution index

Water quality status in this study was assessed using the PI method. The PI method is established based on the Minister of Environment and Forestry Regulation No. 27/2021 on Environmental Quality Index (See Eq. (1)). The regulation classifies water as good, lightly polluted, moderately polluted, and highly polluted (see Table 4) [8].

Table 4. Pollutant index value classification

Pollution Index Value (PI)	Quality Status
0 ≤ PI ≤ 1	Good
1 < PI ≤ 5	Lightly polluted
5 ≥ PI ≤ 10	Moderately polluted
PI ≥ 10	Highly polluted

Based on the same regulatory framework, the PI value was calculated using the following equation :

$$PI = \sqrt{\frac{\left(\frac{C_{ij}}{L_{ij}}\right)_M^2 + \left(\frac{C_{ij}}{L_{ij}}\right)_R^2}{2}} \quad (1)$$

where, *PI*: Pollution index; *C_{ij}*: Concentration of water quality parameter *i* at sampling station *j*; *L_{ij}*: Standards Concentration of water quality; $\left(\frac{C_{ij}}{L_{ij}}\right)_M^2$: Maximum value of $\frac{C_{ij}}{L_{ij}}$; $\left(\frac{C_{ij}}{L_{ij}}\right)_R^2$:

Average value of $\frac{C_{ij}}{L_{ij}}$.

This status is directly linked to pollution load (may be due to increasing population) [9, 10], where higher concentrations increase treatment complexity and cost [11-13]. Beyond financial impacts, tropical rivers are highly vulnerable to seasonal pollution peaks caused by rainfall [14], urbanization, and waste discharge [11, 12, 15]. Even lightly to moderately polluted sources may already require advanced treatment [14], raising costs for utilities.

The dynamics of seasonal variability, urbanization, and

waste discharge underscore the importance of linking water quality monitoring with hydrological and demographic drivers to better anticipate treatment needs and cost highlight the importance of linking water quality monitoring with hydrological and demographic drivers, since pollution loads fluctuate not only by season but also by land use change, wastewater infrastructure, and river self-purification capacity. Therefore, adopting the PI method in tandem with pollution load estimation provides a more holistic framework to evaluate both the status and magnitude of contamination, ensuring that the assessment captures implications for long-term water supply sustainability in IKN.

2.3.2 Water pollution load

The pollution load was assessed using the Water Pollution Load method, based on the State Minister of Environment Decree No. 110/2003 on Guidelines for Determining Assimilative Capacity, issued by the State Ministry of Environment. This method is intended to estimate the levels of pollutants entering the river, which depend on flow conditions and pollutant type, and was calculated using Eq. (2) as follows.

$$BPS = C_{sj} \times Q_s \times f \quad (2)$$

where, BPS: River pollution load (kg/day); C_{sj} : Actual measured concentration of pollutant elements (mg/liter); Q_s : River discharge (m^3/day); f : Conversion factor (0,001).

Together, the PI and pollution load methods provide a dual analytical framework. The PI classifies the status of water quality, while the pollution load quantifies the volume of pollutants entering the river. Within the previously established Input–Throughput–Output framework, these two methods are positioned at the critical interface between input and throughput. By linking raw-water quality conditions (input) with the complexity of treatment processes (throughput) and their implications for service provision (output), the integration of these approaches offers a more robust and comprehensive basis for estimating treatment requirements and associated costs.

2.3.3 The implication for the cost of production

This section analyzes the financial aspects using data from water utilities in Kutai Kartanegara and North Penajam Paser, as a dedicated water utility for IKN Nusantara has not yet been established. The Basic cost of Production (BCP) [1], calculated with Eq. (3), defines the minimum cost per cubic meter of treated water by combining variable costs (VC), overhead costs (OC), volume of production (VP), and volume losses (VL). Determines the baseline cost for producing each unit of water after accounting for losses (see Eq. (3)).

$$BCP = \frac{VC + OC}{VP - (VL \times VP)} \quad (3)$$

where, BCP = Basic cost of production (IDR/ m^3); VC = Variable cost (IDR/ m^3); OC = Overhead cost (IDR/ m^3); VP = Volume of production (m^3/s); VL = Volume losses (m^3/s).

The analysis of production costs focuses on the chemical treatment component, which is directly influenced by raw water quality. Variable costs cover expenses consisting of (1) Chemical (IDR/ m^3); (2) Energy (IDR/ m^3); (3) Maintenance (IDR/ m^3) that scale with output. The chemical cost of production (CCP) was calculated as (See Eq. (4)):

$$CCP = \frac{\sum(D_i \times P_i)}{Q} \quad (4)$$

where, D_i = dosage of chemical i (kg or L), derived from raw water concentration (C_i) and removal efficiency; (2) P_i = unit price of chemical i (IDR/kg or L); (3) Q = treated volume (m^3).

Chemical costs were determined using operational data from existing water utilities in the IKN area, specifically Danum Taka and Tirta Mahakam [1]. Key influencing parameters include high levels of TDS and TSS increase the demand for coagulants such as alum or lime. Elevated BOD and COD raise the need for chlorine for oxidation, while nitrate and coliform levels further amplify disinfection requirements. The following unit cost estimates were adopted from reference [1]:

(1) Chemical (IDR/ m^3) = 386 – 422 IDR/ m^3 (include chemicals required for coagulation, flocculation, disinfection, and pH adjustment);

(2) Energy (IDR 593 – 641/ m^3);

(3) Maintenance (IDR 143 – 192/ m^3).

These values provide a proxy for estimating chemical-driven production costs in IKN.

2.3.4 Simulation of cost sensitivity

To assess the impact of water quality variations on production costs, a cost sensitivity simulation was performed. In this simulation, chemical costs were assumed to vary proportionally with water quality, while energy, maintenance, and other overhead costs were kept constant.

BCP represents the minimum cost of producing a unit volume of water, factoring in variable costs, overhead costs, production volume, and losses. It serves as the baseline for evaluating water production efficiency after accounting for process losses. BCP calculated using Eq. (5) serves as the foundation for evaluating the minimum cost of producing each cubic meter of water, incorporating variable costs (VC), overhead costs (OC), production volume (VP), and volume losses (VL) (See Eq. (5)) [1].

$$BCP = \frac{VC + OC}{VP - (VL \times VP)} \quad (5)$$

where, BCP = Basic cost of production (IDR/ m^3); VC = Variable cost (IDR/ m^3); OC = Overhead cost (IDR/ m^3); VP = Volume of production (m^3/s); VL = Volume losses (m^3/s).

The total unit cost per cubic meter of water is calculated as the sum of variable costs (VC) and overhead costs (OC) divided by the total production volume at the treatment plant. This calculation does not account for physical or non-physical water losses (assumed at 20% of production, WP) [5], because chemical usage occurs regardless of such losses. Thus, the total unit cost is computed as follows (See Eq. (6) and Eq. (7)):

$$TC = \frac{VC + OC}{VP} \quad (6)$$

$$TC = C_{variable} + C_{overhead}$$

$$C_{variable} = C_{chem} + C_{energy} + C_{maintenance}$$

$$TC = (C_{chem} + C_{energy} + C_{maintenance}) + C_{overhead} \quad (7)$$

where, C_{chem} = chemical cost per m^3 (varies with water quality); C_{energy} , $C_{maintenance}$, $C_{overhead}$ = energy, maintenance, and other overhead costs per m^3 (assumed constant).

Chemical cost variation per scenario [16]: Three scenarios were considered: an improved scenario with 30% lower chemical demand, a baseline scenario representing current conditions, and a deteriorated scenario with 30% higher chemical demand (See Eq. (8)-(10)).

$$C_{chem,scenario} = C_{chem,baseline} \times (1 + \Delta\%) \quad (8)$$

where, $\Delta\%$ = the percentage change in chemical usage for the three scenarios (-30% for improved, 0% for baseline, +30% for deteriorated).

Annual cost:

$$AC = TC \times VP_{annual} \quad (9)$$

where, VP_{annual} = annual production volume ($m^3/year$).

Change relative to baseline:

$$\Delta AC = AC_{scenario} - AC_{baseline} \quad (10)$$

3. RESULT AND DISCUSSION

3.1 Results

3.1.1 General conditions

Flow rates at the sampling sites varied between 0.1 and 27 m^3/s . Water samples were collected at depths adjusted to the river water surface, ranging from 0.5 to 3 meters, to represent the actual water column conditions.

3.1.2 Quality status of raw water sources

The results of field measurements for both the Sepaku Semoi Dam (Location A) (Table 5) and Sepaku River Intake (Location B) are presented in Table 6.

Table 5. Sepaku Semoi Dam (Location A)

P	L _{ij}	C _{ij}							
		T1		T2		T3		T4	
		Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec
T	29	33.7	29.1	33.4	27.9	30.1	29.9	31.8	29.3
TDS	1000	119.67	107	146.67	90.67	149.33	141.33	139	83.83
TSS	40	4.17	4.57	4.5	44.56	27.56	47.17	58.5	34.61
C	15	22.01	16.85	20.37	23.64	62.86	80.61	53.51	42.98
S	6	0.06	0.06	0.08	0.05	0.06	0.13	0.08	0.06
pH	6	6.61	7.94	7.45	8.07	7.18	7.48	7.01	8.04
BOD	2	2.76	2.01	2.65	3.04	2.24	3.46	2.65	7.73
COD	10	16.5	16.12	23.12	7.17	40.25	30.64	27.19	24.74
NO ₃	10	0.58	2.45	0.74	14.94	1.11	2.08	1.13	4.87
TC	1000	92	22	94	540	170	8	700	140

(1) P = Parameters; (2) T = Temperature; (3) TDS = Total Dissolved Solids; (4) TSS = Total Suspended Solids; (5) C = Colour; (6) S = Salinity; (7) pH = Potential of Hydrogen (acidity/alkalinity); (8) BOD = Biochemical Oxygen Demand; (9) COD = Chemical Oxygen Demand; (10) NO₃ = Nitrate; (11) TC = Total Coliform.

Table 6. Intake of Sepaku River (Location B)

P	L _{ij}	C _{ij}									
		S1		S2		S3		S4		S5	
		Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec
T	29	31.4	28.6	32.6	27.9	32.8	28.2	31.4	29.9	33.7	30.2
TDS	1000	91.7	133	114.3	88.3	106.3	110.3	80.67	101.3	258	93.7
TSS	40	10.5	570.7	10.42	72.8	15.17	992.7	10.75	813.3	13.5	6
C	15	30.4	73.99	32.18	32.7	32.84	93.51	36.78	124.7	45	45.4
S	6	0.07	0.04	0.07	0.05	0.07	0.05	0.07	0.04	0.18	0.06
pH	6	7.74	7.64	7.57	8.12	7.56	7.94	7.52	7.75	7.74	7.82
BOD	2	3.16	3.4	6.02	2.22	2.86	2.08	5.22	2.19	2.14	6.71
COD	10	9.72	25.64	14.16	12.7	12.25	17.95	11.13	29.47	38.1	22.8
NO ₃	10	1.58	15.31	2.73	14.2	3.06	19.79	3.22	17.36	5.19	2.45
TC	1000	1100	940	3500	260	2400	4500	16000	4500	9200	14

P	L _{ij}	C _{ij}							
		S6		S7		S8		S9	
		Feb	Dec	Feb	Dec	Feb	Dec	Feb	Dec
T	29	32.6	27.6	32.7	27.9	32.3	28.2	32	27.8
TDS	1000	547.7	92.3	1735	84	15112.7	140.8	276.3	1310.3
TSS	40	12.75	77	9.13	832	18.53	147	31.27	168.67
C	15	37.43	37.2	27.43	36	20.04	30.44	23.32	56.05
S	6	0.45	0.05	1.29	0.05	12.21	0.08	22.8	1.08
pH	6	7.33	8.27	7.32	8.18	7.12	8.05	7.38	7.35
BOD	2	6.22	2.41	2.24	6.93	2.04	3.44	3.07	2.22
COD	10	34.16	18.3	64.61	25.2	796.68	14.28	928.3	22.26
NO ₃	10	8.14	17	16.34	13.3	81.87	23.52	121.2	32.84
TC	1000	410	3900	54000	5900	1550	210	120	2200

(1) P = Parameters; (2) T = Temperature; (3) TDS = Total Dissolved Solids; (4) TSS = Total Suspended Solids; (5) C = Colour; (6) S = Salinity; (7) pH = Potential of Hydrogen (acidity/alkalinity); (8) BOD = Biochemical Oxygen Demand; (9) COD = Chemical Oxygen Demand; (10) NO₃ = Nitrate; (11) TC = Total Coliform.

Table 7. Pollutant index (PI)

Points	Latitude	Longitude	Time	C_{ij}/L_{ij} (Maximum)	C_{ij}/L_{ij} (Average)	PI	Status
S1	0°53'16" S	116°45'50" E	Feb	2.53	0.90	1.90	Lightly Polluted
			Dec	6.77	2.10	5.01	Moderately Polluted
S2	0°53'42" S	116°46'21" E	Feb	3.72	1.40	2.81	Lightly Polluted
			Dec	2.69	1.15	2.07	Lightly Polluted
S3	0°53'52" S	116°46'14" E	Feb	2.90	1.14	2.20	Lightly Polluted
			Dec	7.97	2.48	5.90	Moderately Polluted
S4	0°53'57" S	116°46'12" E	Feb	7.02	1.66	5.10	Moderately Polluted
			Dec	7.54	2.59	5.64	Moderately Polluted
S5	0°54'12" S	116°46'11" E	Feb	5.82	1.73	4.29	Lightly Polluted
			Dec	3.63	1.20	2.70	Lightly Polluted
S6	0°54'25" S	116°46'10" E	Feb	3.67	1.40	2.78	Lightly Polluted
			Dec	3.96	1.70	3.05	Lightly Polluted
S7	0°54'44" S	116°46'10" E	Feb	9.66	2.47	7.05	Moderately Polluted
			Dec	7.59	2.54	5.66	Moderately Polluted
S8	0°55'51" S	116°45'40" E	Feb	10.51	3.22	7.77	Moderately Polluted
			Dec	3.83	1.52	2.91	Lightly Polluted
S9	0°57'07" S	116°45'16" E	Feb	10.84	2.79	7.91	Moderately Polluted
			Dec	4.12	2.14	3.29	Lightly Polluted
T1	0°53'53" S	116°51'36" E	Feb	2.09	0.75	1.57	Lightly Polluted
			Dec	2.04	0.65	1.51	Lightly Polluted
T2	0°54'24" S	116°50'50" E	Feb	2.82	0.83	2.08	Lightly Polluted
			Dec	1.99	1.00	1.57	Lightly Polluted
T3	0°54'33" S	116°50'28" E	Feb	4.11	1.20	3.03	Lightly Polluted
			Dec	4.65	1.36	3.43	Lightly Polluted
T4	0°54'57" S	116°50'14" E	Feb	3.76	1.24	2.80	Lightly Polluted
			Dec	3.94	1.35	2.94	Lightly Polluted

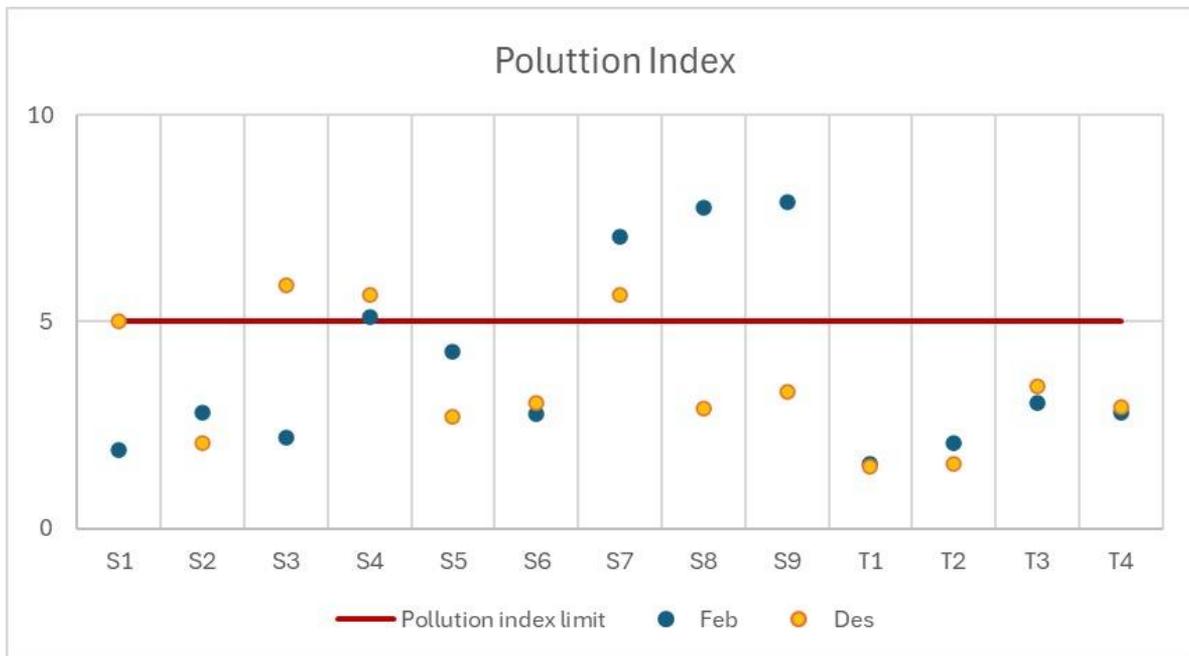


Figure 5. Pollution index (PI) of raw water sources

3.1.3 Water pollution index

Table 7 summarizes the pollution index (PI) values for each sampling station in February and December, including maximum and average C_{ij}/L_{ij} ratios and the resulting water quality classifications based on Regulation No. 27/2021 (see Figure 5).

3.1.4 Water sources pollution load

Using Eq. (2), the results of the water pollution load calculation are presented in Table 7. Specifically, the results for physical parameters are shown in Table 8, for chemical

parameters in Table 9, and for biological parameters in Table 10.

3.1.5 Chemical implications to the cost of production

Based on observations and data collection, the comparative costs across utilities are as follows: Danum Taka shows a chemical cost of IDR 422/m³ with a total production cost of IDR 1,447/m³, reflecting lower chemical expenses but limited by operational inefficiencies and high water losses. Tirta Mahakam has a chemical cost of IDR 386/m³ and a total cost of IDR 5,180/m³, where higher organic and microbial loads

increase chlorine demand, and overhead costs dominate. For the IKN projection [1], the estimated chemical cost is IDR 404/m³ with a total production cost of IDR 3,313.5/m³ [1],

benefiting from economies of scale and improved intake management, though still influenced by seasonal peaks in TDS and nitrate.

Table 8. Physical characteristics of raw water

Points	Latitude	Longitude	Month	T	TDS	TSS	C	S
S1	0°53'16" S	116°45'50" E	Feb	31.4	9.607,68	4.043,52	30.38	5.53
			Dec	28.6	41.368,32	177.501,20	73.99	12.44
S2	0°53'42" S	116°46'21" E	Feb	32.6	90.851,88	2.115,07	32.18	74.65
			Dec	27.9	37.853,29	31.210,86	32.7	21.43
S3	0°53'52" S	116°46'14" E	Feb	32.8	15.804,98	1.440,05	32.84	9.68
			Dec	28.2	366.048,46	3.293.440,82	93.51	165.89
S4	0°53'57" S	116°46'12" E	Feb	31.4	10.699,78	559,87	36.78	7.46
			Dec	29.9	63.035,37	505.956,33	124.7	24.88
S5	0°54'12" S	116°46'11" E	Feb	33.7	239.846,40	1.262,55	44.98	178.33
			Dec	30.2	2.622.160,51	167.961,60	45.42	1.679.62
S6	0°54'25" S	116°46'10" E	Feb	32.6	2.350.322,44	2.882,25	37.43	1.898.90
			Dec	27.6	73.391,27	61.205,76	37.23	39.74
S7	0°54'44" S	116°46'10" E	Feb	32.7	290.318,93	32.849,86	27.43	23.954.23
			Dec	27.9	76.204,80	754.790,40	36.01	45.36
S8	0°55'51" S	116°45'40" E	Feb	32.3	281.234,07	9.792,78	20.04	141
			Dec	28.2	65.677,65	68.584,32	30.44	37.32
S9	0°57'07" S	116°45'16" E	Feb	32	2.052.910,66	62.985,60	23.32	1.119.74
			Dec	27.8	611.347,56	78.694,68	56.05	503.88
T1	0°53'53" S	116°51'36" E	Feb	33.7	2.580,42	476,17	22.01	1.04
			Dec	29.1	741.432,96	31.666,81	16.85	415.76
T2	0°54'24" S	116°50'50" E	Feb	33.4	17.820,65	2.034,78	20.37	13.61
			Dec	27.9	32.902,33	16.169,93	23.64	18.14
T3	0°54'33" S	116°50'28" E	Feb	30.1	2.939,81	419,34	62.86	1.94
			Dec	29.9	3.907,49	1.304,16	80.61	3.59
T4	0°54'57" S	116°50'14" E	Feb	31.8	11.151,82	1.486,08	53.51	9.68
			Dec	29.3	47.803,22	19.736,01	42.98	34.21

Table 9. Chemical characteristics

Points	Latitude	Longitude	Month	pH	BOD	COD	NO ₃
S1	0°53'16" S	116°45'50" E	Feb	7.74	183,17	1.879,51	78,38
			Dec	7.64	1.057,54	7.975,07	4.762,02
S2	0°53'42" S	116°46'21" E	Feb	7.57	1.031,82	5.666,57	1.350,33
			Dec	8.12	951,37	5.442,51	6.081,04
S3	0°53'52" S	116°46'14" E	Feb	7.56	832,2	1.957,89	377,26
			Dec	7.94	6.900,94	59.553,79	65.658,47
S4	0°53'57" S	116°46'12" E	Feb	7.52	88,75	1.579,83	215,2
			Dec	7.75	1.362,36	18.332,70	10.799,31
S5	0°54'12" S	116°46'11" E	Feb	7.74	309,66	8.931,13	2.258,57
			Dec	7.82	187.837,06	638.813,95	68.584,32
S6	0°54'25" S	116°46'10" E	Feb	7.33	317,26	123.899,67	12.731,96
			Dec	8.27	1.915,66	14.570,15	13.512,96
S7	0°54'44" S	116°46'10" E	Feb	7.32	3.225,42	975.325,78	127.356,64
			Dec	8.18	6.286,90	22.825,15	12.029,47
S8	0°55'51" S	116°45'40" E	Feb	7.12	6.486,22	38.781,02	1.370,10
			Dec	8.05	1.604,97	6.662,48	10.973,49
S9	0°57'07" S	116°45'16" E	Feb	7.38	37.091,52	323.662,00	10.315,64
			Dec	7.35	1.035,76	10.385,63	15.321,83
T1	0°53'53" S	116°51'36" E	Feb	6.61	38,71	695,52	19,2
			Dec	7.94	13.927,85	111.699,99	16.976,74
T2	0°54'24" S	116°50'50" E	Feb	7.45	614,3	1.889,96	307,35
			Dec	8.07	1.103,16	2.601,85	5.421,43
T3	0°54'33" S	116°50'28" E	Feb	7.18	79,07	338,63	84,52
			Dec	7.48	95,66	847,13	57,51
T4	0°54'57" S	116°50'14" E	Feb	7.01	721,61	1.538,89	445,27
			Dec	8.04	4.407,96	14.107,74	2.777,07

3.1.6 Simulation of cost sensitivity

Using the average values, a simulation was carried out assuming chemical costs vary proportionally with water quality, while energy, maintenance, and other overhead remain constant [17, 18]. The annual production of IKN

Projection is equal to 157,680,000 m³/year (see Table 11).

This simulation shows that a ±30% shift in chemical demand due to raw water quality fluctuations may alter total annual production costs by approximately ±IDR 19 billion, underscoring the strong sensitivity of chemical expenses to

pollution loads.

3.2 Discussion

3.2.1 Physical parameters (temperature, TDS, TSS, colour, salinity)

The water temperature standard is about 26.3 - 33.1°C, obtained from a 3°C deviation of air temperature (Minister of Health Regulation No. 2 of 2023 concerning Implementation of Government Regulation No. 66 of 2014 concerning Environmental Health). The increase in river temperature due to climate change has an impact on the surrounding ecosystem [19], especially the dissolved oxygen (DO) level, which is one of the important parameters that describes the condition of raw water pollution. Surface temperature will reduce the DO concentration in India by 2.3% [20]. In addition to temperature, DO is also influenced by atmospheric pressure, temperature, salinity, water turbulence, photosynthesis, respiration, and waste [21, 22].

Table 8 presents physical parameters. The TDS load showed a substantial increase at several locations during December. For instance, at S5, the value rose sharply from 239,846.40 in February to 2,622,160.51 in December. A similar trend was observed at S6 and S3, where TDS loads reached 2,350,322.44 and 366,048.46, respectively. This increase in TDS concentration is strongly influenced by intensified human activities near the sampling sites, particularly in densely populated areas with high domestic inputs [23].

TDS is often used in determining the quality of water for consumption [24] because it describes various dissolved solid materials, including organic compounds and colloids [25]. TDS needs to be considered in planning and development [26] to provide clean water to IKN. Both river flows show significantly different TDS values. Flow 2 tends to be more stable below the quality standard, unlike flow 1. The highest TDS values were found at S7 and S8 of 1,735.00 mg/l and 15,112.67 mg/l in February measurements. The high TDS value due to construction causes solids from the riverbed to be lifted to the surface. Although the value decreased in December alongside the completion of construction, Outlet City 1 (S9) still tended to experience an increase in TDS due to the shipping activity, loading, and unloading at the pier that affected the accumulation of mud from the riverbed [10].

The TSS load also displayed a rising trend during the rainy season (December). At S3, TSS reached 3,293,440.82, the highest among all stations. Elevated values were also recorded at S7 (754,790.40) and S8 (68,584.32). High TSS levels can cause turbidity, thereby reducing water quality. The increase is likely linked to ongoing construction activities around the river, which disturb sediments.

The TSS value also fluctuated during the measurement temperature, especially when entering the rainy season. It is aligned with research [27] that the TSS value is also affected by temperature, although with a small impact.

The colour parameters above the quality standards are in line with physical observations during measurements, where all sampling locations are brownish and turbid. Another parameter is salinity, which is below the quality standards during measurements in December. Salinity describes the condition of the river ecosystem and is needed to control components in the water body [28].

Salinity loads generally followed a similar seasonal pattern, increasing during December. At S5, salinity rose significantly from 178.33 ppt in February to 1,679.62 ppt in December.

However, an opposite trend was observed at stations S6 to S9, where salinity decreased in December, indicating localized hydrological or land-use influences.

3.2.2 Chemical parameters (pH, BOD, COD, nitrate)

The chemical parameters revealed spatial and seasonal variability. pH remained relatively stable within the acceptable range of 6–9, though slightly more alkaline conditions were observed in December at S6, S7, and T1.

BOD values showed extreme spikes at S5 (187,837.06 in December) and S9 (37,091.52 in February), reflecting intense organic pollution from domestic wastewater inputs. Other points, such as S7 and T1, also recorded elevated BOD in December, indicating that runoff during the rainy season carried more biodegradable material into rivers [30].

Similarly, COD values peaked at S5 in December (638,813.95) and S7 in February (975,325.78), indicating heavy chemical and organic loads likely due to industrial and domestic waste discharges [31].

Nitrate concentrations were particularly high at S5 (68,584.32 in December) and S3 (65,658.47 in December) [32], far above quality standards. Both stations are near residential zones, where nitrate pollution is often linked to sewage leakage and fertilizer runoff. This pattern is consistent with research [32], which found that centralized residential areas contribute to high NO₃⁻ levels. Even with dilution during the rainy season, hotspots at S8 and S9 still exceeded thresholds, suggesting that rainfall was insufficient to reduce nitrate levels.

Table 9 presents the chemical characteristics of river water across the sampling stations in February and December. The pH values generally remained within the acceptable range of 6–9, showing relatively stable conditions across all stations. However, a slight increase was observed in December, particularly at S6, S7, and T1, indicating more alkaline conditions, possibly due to dilution effects from rainfall or reduced organic input.

Table 10. Biological characteristics of raw water

Points	Month	Total Coliform
S1	Feb	48.384,00
	Dec	292.377,60
S2	Feb	68.014,08
	Dec	111.421,44
S3	Feb	483.840,00
	Dec	14.929.920,00
S4	Feb	381.542,40
	Dec	2.799.360,00
S5	Feb	7.464.960,00
	Dec	391.910,40
S6	Feb	241.056,00
	Dec	3.100.032,00
S7	Feb	126.074,88
	Dec	5.352.480,00
S8	Feb	216.207,36
	Dec	97.977,60
S9	Feb	1.315.699,20
	Dec	1.026.432,00
T1	Feb	2.937,60
	Dec	152.444,16
T2	Feb	213.840,00
	Dec	195.955,20
T3	Feb	66.355,20
	Dec	221,18
T4	Feb	2.211.840,00
	Dec	79.833,60

Table 11. Chemical costs simulation

Scenario	Variable Cost			Overhead Cost	TC (IDR/m ³)	AC (IDR/year)	Δ vs Baseline
	C (IDR/m ³)	E (IDR/m ³)	M (IDR/m ³)	O (IDR/m ³)			
Improved (-30% demand)	282.8	617.0	167.5	2,125.0	3,192.3	503,361,864,000	-19,110,816,000
Baseline	404.0	617.0	167.5	2,125.0	3,313.5	522,472,680,000	0
Deteriorated (+30% demand)	525.2	617.0	167.5	2,125.0	3,434.7	541,583,496,000	+19,110,816,000

(1) C = Chemical (IDR/m³); (2) E = Energy (IDR/m³); (3) M = Maintenance (IDR/m³)

The BOD showed strong spatial and seasonal variations. Extremely high BOD values were recorded at S5 (187,837.06 in December) and S9 (37,091.52 in February), reflecting intense organic pollution likely originating from domestic and settlement activities. Other stations, such as S7 and T1, also recorded notable increases in December, suggesting seasonal runoff transported more biodegradable organic matter into the river.

Similarly, the COD displayed critical spikes at several points, notably S5 in December (638,813.95) and S7 in February (975,325.78), indicating substantial chemical and organic pollutants in the water column. These exceptionally high COD loads point to heavy domestic and possibly industrial contributions, particularly at stations located near densely populated or high-activity areas.

The nitrate (NO₃⁻) concentrations also revealed elevated levels at multiple stations. For example, S5 (68,584.32 in December) and S3 (65,658.47 in December) exceeded typical environmental thresholds. These hotspots correspond to residential areas where nitrate pollution is often linked to sewage leakage, fertilizer runoff, and other anthropogenic discharges. By contrast, some stations (e.g., T2 in February and T3 in December) exhibited relatively low nitrate loads, consistent with less human activity in their surroundings.

Overall, the chemical indicators suggest that both organic and nutrient pollution are significant issues in the study area, with December generally showing higher values than February. This seasonal difference highlights the influence of rainy season runoff and land-based activities in amplifying the pollution load. The consistently high BOD, COD, and NO₃ values at certain stations underscore the need for targeted mitigation strategies, particularly in densely populated and high-activity zones.

3.2.3 Biological parameters (total coliform)

Total coliform was the only biological indicator measured. The highest value was observed at S3, with an increase from 483,840.00 MPN/100 mL in February to 14,929,920.00 MPN/100 mL in December. Elevated coliform counts were also recorded at S5 and S6, underscoring that untreated domestic waste significantly contaminates the river [9].

While some points showed reductions during the rainy season due to dilution, almost all locations remained well above the maximum standard, especially S3, S4, S6, and S7. The link between coliform levels and physical-chemical parameters is evident: optimal bacterial growth occurs at pH ~7 and temperature around 37°C [10]. In addition, increases in BOD and COD promote bacterial proliferation, highlighting serious health risks from microbial pollution.

Table 10 presents the biological characteristics of river water, where total coliform was the only microbiological parameter analysed in this study. Total coliform is a widely recognized indicator of microbiological pollution and reflects

contamination from both human and animal waste.

Total coliform was the only biological parameter measured in this study. The highest total coliform value was recorded in S3, reaching 14,929,920.00 MPN/100mL in December, a significant increase compared to February at 483,840.00 MPN/100mL. In addition, S5 and S6 also showed high values. This indicates that domestic waste has not been properly processed before entering the river. High coliform content is a significant indicator of water pollution in urban and densely populated areas [11].

Overall, pollution load values increased during the rainy season (December), particularly for TDS, TSS, and total coliform at stations S3, S5, S6, and S7. This seasonal rise reflects the combined effects of intensified runoff, domestic discharge, and construction-related disturbances, which amplify the pollutant load carried into the river. Chemical indicators such as BOD, COD, and nitrate further confirm the strong influence of anthropogenic inputs, especially in densely populated and high-activity areas. Researcher [32] also stated that river water quality tends to deteriorate in the rainy season due to increased water discharge carrying suspended particles and various other pollutants.

3.2.4 Integrated assessment: Pollution index and pollution load

The PI assessment classified water quality status across stations from lightly polluted to moderately polluted. February conditions generally showed lighter pollution, whereas December values tended to worsen, with several points (e.g., S3, S4, S7, S8, S9) falling into the moderately polluted category. These fluctuations underscore the influence of seasonal rainfall, runoff, and local land use.

Pollution Load analysis further quantifies pollutant volumes entering the river system. The combined use of PI (qualitative status) and Pollution Load (quantitative load) provides a robust framework to evaluate water quality deterioration, identify hotspots, and prioritize interventions. This dual approach ensures that both the status and magnitude of pollution are captured.

All sampling locations indicated that the river water was classified as lightly to moderately polluted based on the PI results. Flow 2 (T1–T4) tended to show more stable conditions compared to Flow 1 (S1–S9), which exhibited greater fluctuations across seasons. This suggests that Flow 2 is relatively safer to be considered as a raw water source for IKN. However, the increasing PI values observed at most Flow 2 stations also indicate that the pollution load is gradually rising over time. While several sampling points demonstrated improvements or maintained their water quality, others experienced worsening conditions. These dynamics are influenced by the river's natural self-purification capacity and the role of meanders that enhance quality along the stream [10]. Therefore, integrated water quality management across both

flows is crucial, particularly in the context of growing population pressures and the relocation of Indonesia's capital to Nusantara (IKN) [9]. Such management should include periodic monitoring of key water quality parameters [33], further investigations, and strategic planning for pollution control.

3.2.5 Implications of quality status on water treatment costs

The exceedance of water quality standards for parameters such as TDS, TSS, BOD, COD, nitrate, and coliform indicates that advanced treatment is required for raw water in Nusantara. Even sampling points classified as lightly polluted may necessitate additional treatment steps—such as coagulation, filtration, and disinfection—that directly increase operational costs. Seasonal peaks observed during December highlight the need for flexible treatment capacity to accommodate higher pollutant loads. Failure to adapt treatment to these fluctuations would not only compromise public health but also escalate long-term costs for utilities.

Water quality status has a direct influence on both the complexity and cost of treatment. The more pollutants present, the more advanced and costly the treatment process required. Parameters exceeding standards (e.g., TDS, TSS, COD, NO_3 , and coliform) necessitate additional processes beyond conventional sedimentation and filtration. Technologies such as ozonation, activated carbon, and enhanced disinfection may be needed to achieve potable water quality.

Previous studies [4] emphasize the importance of selecting treatment technologies that balance effectiveness with affordability, ensuring access for the wider community. Treatment costs are highly sensitive to raw water chemistry because chemicals (coagulants, lime, chlorine) represent one of the largest variable cost components [4]. The quality of the raw water source affects the cost of water treatment due to the need for chemicals, including coagulants. Worse raw water source quality needs more chemicals and advanced processing technology.

Poorer water quality directly increases chemical dosage requirements, which in turn raises operating costs. For example, elevated TDS and TSS drive higher alum/lime demand, while BOD and COD require greater chlorine dosing. Excessive nitrate and coliform further amplify disinfection requirements.

Comparative analysis confirms this relationship:

1. Tirta Mahakam faces the highest chemical burden due to urban catchment inputs (COD, coliform), resulting in chemical costs of ~IDR 386/m³ within a total production cost of IDR 5,180/m³.
2. Danum Taka incurs slightly higher chemical costs (~IDR 422/m³) but lower total production costs (IDR 1,447/m³), though still vulnerable to seasonal TSS and BOD surges.
3. IKN projection benefits from economies of scale and improved intake location, with average chemical costs of ~IDR 404/m³ and total costs of ~IDR 3,313.5/m³. However, rainy season fluctuations in TDS, nitrate, and coliform remain a critical challenge.

The simulation further demonstrates that chemical costs alone can shift total production expenses by approximately ±IDR 19 billion/year under different raw water quality scenarios. This finding underscores that upstream pollution control—through wastewater management and catchment protection—is just as important as treatment plant

optimization. Every reduction in pollutant load directly translates into lower chemical expenditure, greater financial sustainability, and more affordable tariffs for consumers in Nusantara.

4. CONCLUSIONS

The findings of this study demonstrate that variation in raw water quality and pollution load along the Sepaku River significantly influences both the complexity of treatment processes and the associated production costs. Elevated concentrations of physical, chemical, and biological parameters—particularly TDS, TSS, BOD, COD, nitrate, and total coliform—were frequently observed to exceed national water quality standards. These exceedances directly increase the need for coagulation, filtration, advanced disinfection, and in some cases, specialized treatment technologies such as ozonation or activated carbon. Seasonal fluctuations, especially during the rainy season, exacerbate these challenges by amplifying turbidity, organic matter, and microbial contamination, thereby requiring flexible and resilient treatment capacities.

From a financial perspective, the study confirms that raw water chemistry is the most direct driver of variable production costs, particularly chemical expenses. Comparative analysis shows that utilities with poorer source water quality, such as PDAM Tirta Mahakam, face higher chemical costs and narrower financial margins, while those with better intake conditions and higher efficiency, such as PDAM Danum Taka, incur lower costs. The projected IKN system benefits from economies of scale and intake selection, with baseline chemical costs of ~IDR 404/m³ and total production costs of ~IDR 3,313.5/m³. However, simulation results indicate that seasonal degradation of raw water quality can increase annual costs by up to IDR 19 billion, highlighting the financial vulnerability of the system to pollution peaks.

To ensure affordable and sustainable drinking water provision for Nusantara, an integrated management strategy is required that links upstream pollution control with downstream treatment optimization. Key components include:

1. Catchment protection and wastewater management, reducing pollutant loads from settlements, agriculture, and construction before they reach intake points.
2. Adaptive treatment processes, capable of adjusting chemical dosing and process intensity during seasonal peaks without compromising public health or financial viability.
3. Periodic water quality and pollution load monitoring, linked to the PI and pollution load calculations, to anticipate treatment needs and costs.
4. Strategic intake siting and infrastructure design, leveraging cleaner flow segments (e.g., Flow 2) and modernized facilities to reduce reliance on expensive advanced treatment.

By combining upstream pollution control with efficient treatment plant management, Nusantara can contain chemical and operational costs while safeguarding water quality. This integrated approach ensures that the future capital city's water supply system remains financially sustainable, technically resilient, and socially equitable, meeting the growing demand for safe drinking water.

AUTHOR CONTRIBUTION

Conceptualization and methodology: Nicco Plamonia (N.P.), Raissa Anjani (R.A.), and Khaerul Amru (K.A.); Investigation: Riardi Pratista Dewa (R.P.D.), R.A., and K.A.; Discussion and writing: R.A., K.A., Budi Kurniawan (B.K.), Ikhsan Budi Wahyono (I.B.W.), Muhammad Komarudin (M.K.), Mohammad Zaidan (M.Z.), Bambang Winarno (B.W.), Syaefudin (S.), and Wahyu Purwanta (W.P.); Editing and review: Teddy W. Sudinda (T.W.S.), Nicko Widiatmoko (N.W.), Hidir Tresnadi (H.T.), Tito Eko Parato (T.E.P.), and Muktiyono (M.). All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENT

The study was funded by RIIM-3 2023 LPDP, Indonesia (Indonesia Endowment Fund for Education) for financing the research, and BRIN, Indonesia (Badan Riset and Innovation National, Indonesia) for providing office and discussion.

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