



Pollution Constraints on Raw-Water Security in the Air Bengkulu Watershed: Linking Water-Quality Exceedances, Pollutant Loads, and Service Delivery

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ABSTRACT: Raw-water security in urban watersheds depends on the interaction among hydrological potential, source-water quality, and the capacity of water-supply systems to deliver reliable services. This study developed a source-to-service diagnostic framework for the Air Bengkulu Watershed, Indonesia, integrating 90% dependable flow (Q90), normative domestic water demand, actual piped-water delivery, regulatory water-quality exceedances, and event-based pollutant transport. The results showed that dependable flow substantially exceeded normative domestic water demand, whereas actual household piped-water delivery accounted for only 38.0% of the estimated demand. This ratio was interpreted as an indicator of service delivery relative to planning requirements rather than a measure of household coverage or total water availability. Across three monitoring campaigns conducted in 2025, downstream water quality consistently exceeded Class II regulatory thresholds for organic pollutants, nutrients, oil and grease, and faecal contamination indicators. Event-based calculations further demonstrated that pollutant transport varied substantially with river discharge, highlighting the limitations of assessing pollution solely through concentration measurements. The main novelty of this study lies in integrating hydrological potential, pollutant loads, flow-dependent transport, and actual water-service delivery within a unified source-to-service assessment framework. The findings emphasize the importance of risk-based pollution control, flow-synchronized water-quality monitoring, improved intake management, and treatment preparedness. The proposed framework supports more informed water-resource management without assuming that all dependable river flow is directly available for abstraction, treatment, or household distribution.

KEYWORDS: Dependable flow; sewage pressure; treatment resilience; tropical catchment

1. Introduction

Water security in urban watersheds depends not only on hydrological availability but also on source-water quality and the capacity of water-supply systems to deliver reliable services. Assessments based solely on river discharge may overestimate the amount of water available for practical use, particularly when pollution limits abstraction and treatment. Recent global

studies have demonstrated that incorporating water quality into quantity-based assessments substantially increases estimated water-scarcity exposure, while effective pollution-control measures can reduce future water-security risks [1, 2]. Therefore, sustainable raw-water management requires an integrated assessment of water availability, pollution constraints, and service-delivery capacity rather than relying exclusively on hydrological indicators.

At the watershed scale, water-quality deterioration is influenced by interactions among pollutant inputs, land use, runoff, environmental assimilative capacity, and hydrological variability. Previous studies have demonstrated that non-point source pollution is closely associated with environmental capacity [3], while riverine phosphorus transport is influenced by anthropogenic activities, hydroclimatic conditions, and land-use characteristics [4]. Agricultural and urban activities also contribute distinct nutrient, chloride, and microbial contamination patterns [5–10]. These pressures may be intensified by mining activities and rapid landscape changes, particularly in tropical watersheds [11]. Furthermore, point and diffuse pollution sources differ in pollutant composition, transport mechanisms, and potential ecological toxicity [12–14]. Collectively, these findings highlight the importance of managing domestic wastewater, urban runoff, agricultural discharges, and disturbed land as interconnected sources of raw-water contamination.

Identifying pollutant sources and understanding their transport mechanisms remain major challenges in watershed management. River-water concentrations reflect the combined influence of multiple upstream activities, making pollution-source identification difficult without spatial, temporal, and hydrological information. Recent studies have employed inverse modelling [15], time-series and receptor-based approaches [16], multiple faecal contamination indicators [17], and microbial source-tracking techniques [18] to improve pollutant-source identification. Moreover, receiving waters may retain microbial contamination and antibiotic-resistance risks even after conventional wastewater treatment [19]. These findings indicate that conventional concentration-based monitoring alone may be insufficient to characterize pollution risks, particularly when river discharge varies substantially between monitoring events.

For raw-water supply systems, pollution transport and treatment requirements are closely interconnected. Rainfall events can increase pollutant concentrations and treatment demands [20], while hydrometeorological monitoring can improve early-warning capabilities for source-water deterioration [21]. Integrated risk management from source to distribution is increasingly recognized as essential for maintaining drinking-water security under changing climatic conditions [22]. Previous studies have also demonstrated the effects of rainfall intensity and catchment characteristics on pollutant loading [23], the spatial variation of urban pollution along river networks [24], and the potential of integrated monitoring systems to support pollution identification and emergency responses [25]. Basin-scale assessments further indicate that anthropogenic pollution pressures frequently intensify downstream [26]. Recent advances in source apportionment [27], source-to-intake transport modelling [28], runoff pretreatment [29], and source-to-tap water-quality monitoring [30] provide additional opportunities to connect watershed pollution management with water-supply operations.

The Air Bengkulu Watershed, Indonesia, faces similar challenges associated with land-use changes, watershed degradation, altered hydrological conditions, and increasing runoff pressures. Previous investigations have documented these environmental changes and identified substantial dependable-flow potential within the watershed [31–35]. However, an

important research gap remains in understanding how hydrological availability, water-quality deterioration, pollutant transport, and actual water-service delivery interact within a single watershed management framework. Existing assessments have generally examined dependable flow, domestic water demand, water-quality compliance, or water-supply performance separately. Consequently, high hydrological potential may be interpreted as sufficient water availability without considering pollution-related treatment requirements or limitations in service delivery. Similarly, concentration-based assessments may overlook the influence of river discharge on pollutant transport. This fragmented approach limits the ability of watershed managers to identify the combined constraints affecting raw-water security.

To address this gap, this study aims to develop an integrated source-to-service assessment framework for evaluating raw-water security in the Air Bengkulu Watershed. Specifically, the study seeks to quantify hydrological potential using 90% dependable flow (Q90) relative to normative domestic water demand, assess the difference between estimated demand and actual piped-water delivery, identify regulatory water-quality exceedances, and evaluate event-based pollutant transport using concurrent discharge and concentration measurements. The framework integrates hydrological, water-quality, pollution-transport, and water-service indicators to provide a more comprehensive understanding of raw-water security.

The novelty of this study lies in linking hydrological potential, regulatory pollution constraints, flow-weighted pollutant transport, and actual water-service delivery within a unified source-to-service diagnostic framework. Unlike conventional assessments that evaluate water quantity, water quality, or service performance independently, the proposed approach examines their combined implications for watershed management. This integration provides a practical basis for identifying pollution-control priorities, improving source-water monitoring, supporting intake and treatment preparedness, and strengthening water-supply planning. The findings emphasize that sustainable raw-water security requires coordinated wastewater management, runoff control, and water-supply operations, while recognizing that dependable river flow does not necessarily represent water that is immediately abstractable, treatable, or delivered to households.

2. Materials and Methods

2.1. Study Area and Analytical Perspective.

The analysis concerns the Air Bengkulu Watershed in Bengkulu Province, Indonesia, with particular relevance to the middle-to-lower river system that supports downstream urban water use. The watershed drains toward Bengkulu City and receives cumulative pressures from land-use change, settlements, agriculture, plantation activities, mining, urban drainage, and other economic activities. Published watershed studies indicate substantial land-cover change and altered hydrological response, supporting the need to evaluate water supply as a coupled quantity-quality-service problem rather than as a purely hydrological balance [31–33]. The analytical design deliberately separates three concepts. “Hydrological potential” refers to dependable river flow and should not be equated with an abstractable or treatable volume. “Service realisation” refers to water actually distributed through the piped supply system. “Water-quality burden” refers to the degree to which monitored river quality departs from applicable benchmarks and therefore increases ecological, treatment, or health-related pressure. These three evidence layers are interpreted jointly but are not collapsed into a single

score, because doing so would require assumptions about environmental-flow reservations, abstraction permits, treatment yield, non-revenue water, and household use of alternative sources that are not fully available in the present dataset.

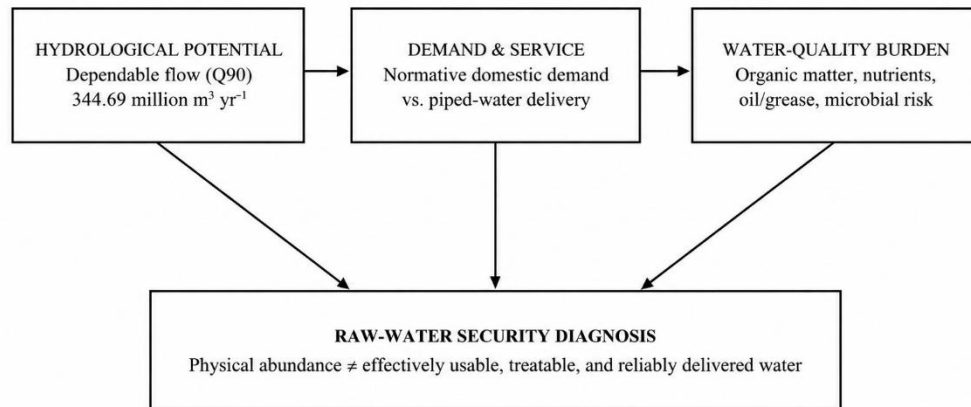


Figure 1. Integrated Diagnostic Framework Used to Distinguish Hydrological Potential, Service Realisation, and Water-Quality Burden in the Air Bengkulu Raw-Water System.

2.2. Data sources.

The study integrates official and published evidence from multiple sources. Population data for Bengkulu City refer to Semester II of 2024 and report 400,533 residents [36]. Urban water-supply statistics for 2024 report 7,950,734 m³ distributed to all customer categories, including 6,665,906 m³ to households [37–39]. Dependable river flow is taken from Khalik et al., who estimated $Q_{90} = 10.93 \text{ m}^3 \text{ s}^{-1}$ using a Weibull flow-duration approach [35]. The water-quality concentration data and 2024 discharge observations used in this study were obtained from Balai Wilayah Sungai Sumatera VII (BWS Sumatera VII), Bengkulu, as official monitoring records for the upstream and downstream stations of the Air Bengkulu River. The 2025 chemistry and microbiology data were also obtained from BWS Sumatera VII, Bengkulu, and are documented in laboratory certificates issued by the UPTD Environmental Laboratory of the Bengkulu City Environmental Agency for samples collected by BWS Sumatera VII [40–42].

Table 1. Evidence Domains and Datasets Used in The Integrated Raw-Water Security Diagnosis.

Evidence domain	Variable(s)	Reference period	Analytical role
Hydrological potential	$Q_{90} = 10.93 \text{ m}^3 \text{ s}^{-1}$ (≈ 344.69 million m ³ yr ⁻¹)	Published 2025 study	Dependable-flow benchmark
Demographic demand	Population = 400,533; 120 L capita ⁻¹ day ⁻¹	2024 population	Normative domestic demand
Piped-water service	Total = 7,950,734 m ³ yr ⁻¹ ; household = 6,665,906 m ³ yr ⁻¹	2024	Service-realisation diagnostic
Water quality	BOD, COD, TSS, DO, nitrate, total phosphate, oil & grease, fecal coliform	Apr, Jul, Oct 2025	Event-specific regulatory exceedance and potential source-water treatment pressure
Event transport	Concurrent discharge + concentration for selected parameters	Feb and May 2024	Event-based pollutant-load estimation

2.3. Hydrological availability and normative domestic demand

The hydrological analysis uses Q_{90} as a conservative dependable-flow indicator. Q_{90} represents the discharge equalled or exceeded approximately 90% of the time in the underlying flow-duration analysis and therefore provides a more relevant planning benchmark than an

annual mean flow. The daily- and annual-equivalent volumes were calculated from Q90 for comparison with demand, while recognising that these equivalent volumes are not estimates of legally or technically abstractable yield. The annual-equivalent dependable-flow volume was calculated using Eq. (1).

$$V_{Q90} = Q_{90} \times 86,400 \times 365 \quad (1)$$

Basic domestic demand was estimated using the 2024 population and a planning value of 120 L capita⁻¹ day⁻¹ derived from the Indonesian spatial water-resource accounting standard [38]. This value is used as a normative planning benchmark for scenario comparison, not as an observation of current per-capita household consumption in Bengkulu City. Because household meter-level consumption and non-piped water-use data were not available, the 120 L capita⁻¹ day⁻¹ value should be interpreted as a standardised demand assumption that permits comparison between hydrological potential and formal service delivery, rather than as evidence that every resident currently consumes this volume. Domestic demand was calculated using Eq. (2).

$$D_{\text{dom}} = P \times q \quad (2)$$

A transparent hydrological availability ratio (HAR) was calculated as Q90 divided by the equivalent domestic-demand discharge. HAR is used strictly as a diagnostic ratio between dependable river-flow potential and normative domestic demand. It is not a direct measure of water physically available for abstraction, treatment, distribution, or household access because environmental-flow requirements, competing withdrawals, intake constraints, treatment yield, and network limitations are not embedded in the ratio. The HAR formulation is given in Eq. (3).

$$\text{HAR} = \frac{Q_{90}}{Q_{\text{dom}}} \quad (3)$$

2.4. Service-realisation Diagnostic.

The 2024 piped-water statistics were compared with normative domestic demand to diagnose how far formal delivery approaches the planning benchmark. Household distributed volume was divided by normative domestic demand to obtain a household piped-service realisation ratio (PSR). This metric represents a volume-to-norm comparison. It is conceptually distinct from service coverage (the proportion of people or connections served), actual household water consumption, and total water availability in the watershed. Total system delivery was also reported for context, but because it includes non-household users, it is not treated as a direct household indicator. The household piped-service realisation ratio was calculated using Eq. (4).

$$\text{PSR}_{\text{household}} = \frac{V_{\text{household,distributed}}}{D_{\text{domestic}}} \quad (4)$$

A PSR below 1 should not be interpreted as a physical water deficit, the fraction of households lacking water, or the proportion of the population covered by the utility. Households may use wells, groundwater, purchased water, or other non-piped sources, and the available dataset does not quantify these volumes. The 38.0% value therefore indicates only that recorded household piped-water delivery was equivalent to 38.0% of the normative

domestic-demand volume used in this study. It is a diagnostic of formal service realisation relative to a planning norm, not a direct measure of household water-access coverage, consumption, or total basin water availability.

2.5. *Water-Quality Constraint Analysis.*

The 2025 laboratory certificates provide paired upstream-downstream observations for 30 April, 10 July, and 29 October 2025 and explicitly state Class II benchmarks under Bengkulu Provincial Regulation No. 6/2005 [39–42]. These three campaigns provide event-specific evidence from separated periods of the year, but they do not constitute continuous or seasonally complete monitoring. Accordingly, exceedances are interpreted as repeated observations during the monitored events and are not extrapolated to annual exceedance frequencies or year-round water-quality conditions. The principal treatment-relevant parameters were BOD (3 mg L⁻¹), COD (25 mg L⁻¹), total phosphate (0.2 mg L⁻¹), oil and grease (1 mg L⁻¹), and fecal coliform (5,000 MPN 100 mL⁻¹). TSS, nitrate, pH, and dissolved oxygen were retained for supporting interpretation. For parameters with a maximum standard, the benchmark-exceedance factor was calculated using Eq. (5).

$$EF = \frac{C_{\text{observed}}}{C_{\text{benchmark}}} \quad (5)$$

An $EF > 1$ indicates exceedance. Mean EF values across the three 2025 campaigns were used only to summarise the relative magnitude of benchmark departure at the monitored stations. They are interpreted as indicators of potential raw-water quality pressure, not as measured treatment-plant impacts. No treatment-plant operating data (e.g., coagulant dose, energy use, filter run time, sludge production, treatment yield, or finished-water compliance) were available. Consequently, the study does not convert exceedance into an assumed loss of raw-water volume or claim a quantified treatment penalty.

2.6. *Event-Based Pollutant Transport.*

For 29 February and 6 May 2024, the monitoring records report both river discharge and concentrations, allowing event-based transport estimates for BOD, COD, TSS, nitrate, and total phosphate. The event-based daily-equivalent pollutant load was calculated using Eq. (6).

$$L = C \times Q \times 86.4 \quad (6)$$

where L is the estimated load in kg day⁻¹, C is concentration in mg L⁻¹, Q is discharge in m³ s⁻¹, and 86.4 is the unit-conversion factor. These values are interpreted as event-specific transport estimates only. Because load is the product of concentration and discharge, upstream-downstream differences reflect the combined effect of water-quality concentration and flow magnitude and cannot be attributed to changes in pollution-source intensity alone. They are not annual loads and are not used as a closed-reach mass balance because the records do not establish identical sampling time, travel time, hydrograph phase, cross-section comparability, or continuous discharge conditions between stations.

2.7. Data-Quality and Interpretation Rules.

The study follows conservative data-quality rules. Reported values were retained as documented unless they were physically implausible and not needed for this article. The September 2024 upstream record contains implausible pH and dissolved-oxygen values; these variables were therefore not used. The 2025 oil-and-grease records were harmonised to mg L^{-1} when necessary. No missing values were imputed. Most importantly, the analysis does not infer effective raw-water yield by subtracting arbitrary fractions from Q90. Environmental-flow requirements, competing abstractions, treatment losses, intake constraints, and non-revenue water must be measured explicitly before a defensible effective-yield model can be constructed.

3. Results and Discussion

3.1. Hydrological Potential Relative to Normative Domestic Demand.

The hydrological assessment indicated that the Air Bengkulu Watershed had substantial dependable-flow potential relative to its estimated domestic water demand. The 90% dependable flow (Q90) was $10.93 \text{ m}^3 \text{ s}^{-1}$, equivalent to approximately $944,352 \text{ m}^3 \text{ day}^{-1}$ or $344.69 \text{ million m}^3 \text{ yr}^{-1}$. Based on the 2024 population of 400,533 inhabitants and a normative water-demand coefficient of $120 \text{ L capita}^{-1} \text{ day}^{-1}$, basic domestic water demand was estimated at $48,064 \text{ m}^3 \text{ day}^{-1}$, corresponding to $0.556 \text{ m}^3 \text{ s}^{-1}$ or $17.54 \text{ million m}^3 \text{ yr}^{-1}$. The resulting hydrological availability ratio (HAR) was 19.65, indicating that dependable river discharge was approximately 19.65 times the equivalent normative domestic-demand discharge under the adopted assumptions. Although this ratio suggests substantial hydrological potential, it should not be interpreted as evidence that the entire dependable flow is available for abstraction or that domestic water requirements are fully satisfied. Actual raw-water availability depends on environmental-flow requirements, competing water uses, intake capacity, treatment efficiency, operational limitations, and source-water quality. These factors were not deducted from Q90 because the necessary quantitative information was unavailable. Therefore, the calculated HAR represents a physical-flow benchmark rather than an estimate of usable or deliverable water. The relationship among dependable-flow potential, normative domestic demand, and actual piped-water delivery is illustrated in Figure 2.

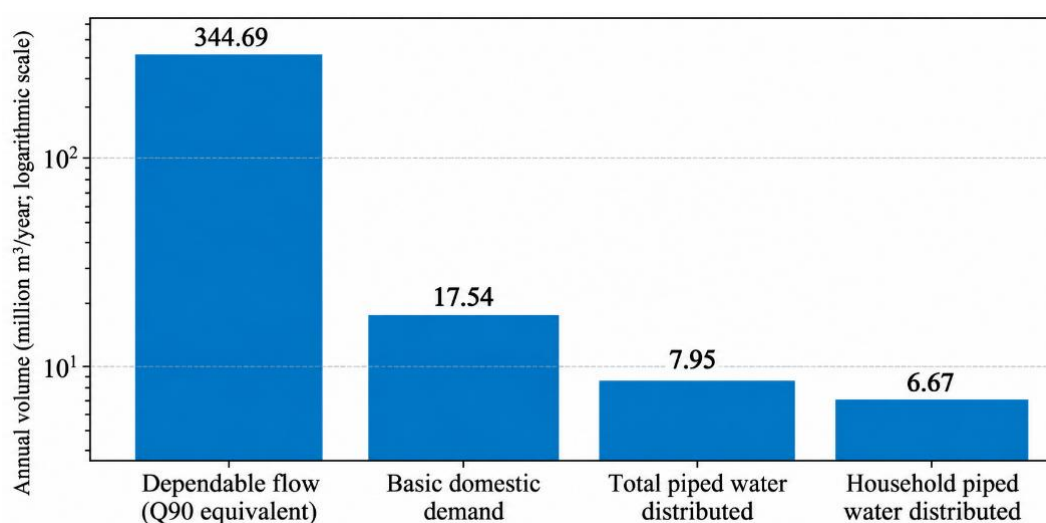


Figure 2. Annualised Dependable-Flow Equivalent, Normative Basic Domestic Demand, and Realised Piped-Water Delivery in 2024,

The annualized Q90 equivalent was substantially greater than both the estimated domestic demand and recorded piped-water delivery. A logarithmic scale was adopted to accommodate these differences in magnitude and facilitate comparison. The figure highlights the distinction between the volume of water potentially present in the river system and the considerably smaller volume delivered through the formal water-supply network.

The corresponding hydrological and service-delivery indicators are summarized in Table 2. Although the annualized dependable-flow equivalent reached 344.69 million m³, normative domestic demand was only 17.54 million m³, while household piped-water delivery amounted to 6.67 million m³. These differences indicate that aggregate river-water volume alone cannot explain the limitations of the existing water-supply system. However, the available data do not establish how much of the dependable flow could be sustainably abstracted, treated, or distributed. Consequently, hydrological potential and actual service delivery must be evaluated separately when assessing raw-water security.

Table 2. Quantity and Service Diagnostics for the Air Bengkulu Raw-Water System.

Metric	Value	Interpretation
Q90 dependable flow	10.93 m ³ s ⁻¹	Hydrological potential, not directly abstractable yield
Q90 annual-equivalent volume	344.69 million m ³ yr ⁻¹	Physical river-flow benchmark
Normative basic domestic demand	48,064 m ³ day ⁻¹ (17.54 million m ³ yr ⁻¹)	400,533 inhabitants × 120 L capita ⁻¹ day ⁻¹
Hydrological availability ratio	19.65	Diagnostic ratio, not abstractable or delivered water
Total piped water distributed	7.95 million m ³ yr ⁻¹	All customer categories
Household piped water distributed	6.67 million m ³ yr ⁻¹	Household category only
Household service realization	38.0%	Household piped delivery relative to normative demand; not service coverage
Total distribution/domestic demand	45.3%	Contextual comparison only; includes non-household users

3.2. Piped-Service Realization and the Source-to-Service Gap.

The 2024 water-supply records revealed a substantial difference between normative domestic water demand and actual piped-water delivery. As presented in Table 2, the Bengkulu City water-supply system distributed approximately 7.95 million m³ of water across all customer categories, of which 6.67 million m³, or 83.84%, was delivered to household customers. Household piped-water delivery was equivalent to approximately 18,263 m³ day⁻¹, considerably lower than the estimated normative domestic demand of 48,064 m³ day⁻¹. Accordingly, the household piped-service realization ratio was 38.0%. This ratio represents the volume of water distributed to household customers relative to the normative domestic-demand benchmark. It does not indicate that only 38.0% of households were connected to the water-supply network or that the remaining 62.0% lacked access to water. Similarly, it does not represent actual per-capita consumption or the proportion of total water resources available for domestic use. These distinctions are important because distributed water volume, household consumption, service coverage, and raw-water availability represent different aspects of water-supply performance.

The observed difference between normative demand and household piped-water delivery highlights a source-to-service gap that cannot be explained by hydrological availability alone. Although dependable river discharge substantially exceeded the estimated domestic requirement, formal household delivery remained considerably below the normative planning

benchmark. This finding suggests that factors beyond aggregate river flow may influence water-service performance. Potential constraints include intake and treatment capacity, storage availability, pumping efficiency, distribution-network coverage, non-revenue water, household connections, and interruptions associated with raw-water quality. However, the available dataset did not contain sufficient operational information to quantify the individual contributions of these factors. Therefore, the observed service-realization gap should be interpreted as a diagnostic indicator rather than direct evidence of infrastructure failure, treatment limitations, or insufficient household coverage. Further utility-level investigations incorporating production records, treatment performance, distribution losses, connection data, and household consumption would be required to identify the underlying causes.

3.3. Persistent Water-Quality Exceedances and Potential Treatment Pressure.

Water-quality monitoring revealed recurring contamination at the downstream station during the three sampling campaigns conducted on 30 April, 10 July, and 29 October 2025. The monitoring results indicated simultaneous exceedances of the applicable Class II benchmarks for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphate, oil and grease, and fecal coliform. Upstream conditions were comparatively less impaired, although several parameters also exceeded their respective regulatory thresholds. The spatial and temporal differences in water quality are presented in Table 3, which summarizes the concentrations of the five principal indicators at the upstream and downstream stations. Upstream BOD and total phosphate exceeded their benchmarks during all three monitoring events, whereas COD exceedances occurred in July and October. In contrast, upstream oil and grease and fecal coliform remained below their respective limits throughout the monitoring period. Downstream concentrations consistently exceeded the applicable benchmarks for all five indicators, suggesting greater pollution pressure in the lower river section during the sampled events.

Table 3. Date-specific upstream and downstream concentrations of principal Class II water-quality parameters in the Air Bengkulu River, 2025.

Date	Segment	BOD (mg/L)	COD (mg/L)	Total P (mg/L)	Oil and grease (mg/L)	Fecal coliform (MPN/100 mL)
30 Apr 2025	Upstream	4.00*	21.0	0.322*	0.450	2,400
30 Apr 2025	Downstream	9.00*	44.0*	2.350*	1.540*	5,400*
10 Jul 2025	Upstream	5.00*	28.0*	0.414*	0.320	1,100
10 Jul 2025	Downstream	8.00*	47.0*	2.520*	1.630*	5,400*
29 Oct 2025	Upstream	5.00*	30.0*	0.668*	0.568	840
29 Oct 2025	Downstream	10.00*	68.0*	2.270*	2.410*	5,400*

Note: Values marked with an asterisk (*) exceeded the applicable Class II benchmarks stated in the monitoring certificates [39–42]. Concentrations are expressed in mg L⁻¹, except fecal coliform, which is reported as MPN 100 mL⁻¹.

As shown in Table 3, downstream BOD concentrations ranged from 8 to 10 mg L⁻¹, while COD ranged from 44 to 68 mg L⁻¹. Total phosphate concentrations varied between 2.27 and 2.52 mg L⁻¹, and oil and grease concentrations ranged from 1.54 to 2.41 mg L⁻¹. Fecal coliform remained at 5,400 MPN 100 mL⁻¹ during all three monitoring campaigns. These findings

demonstrate recurring downstream contamination involving organic matter, nutrients, oil and grease, and microbial indicators.

To further assess the magnitude of regulatory exceedances, the measured concentrations were compared with their respective Class II benchmarks using exceedance factors (EFs). The resulting upstream and downstream exceedance patterns are illustrated in Figure 3. Across the three monitoring events, mean downstream BOD was 9.0 mg L⁻¹ (EF = 3.00), COD was 53.0 mg L⁻¹ (EF = 2.12), total phosphate was 2.38 mg L⁻¹ (EF = 11.90), and oil and grease averaged 1.86 mg L⁻¹ (EF = 1.86). Total phosphate exhibited the greatest relative departure from its regulatory benchmark, indicating that nutrient contamination was particularly pronounced at the downstream monitoring location.

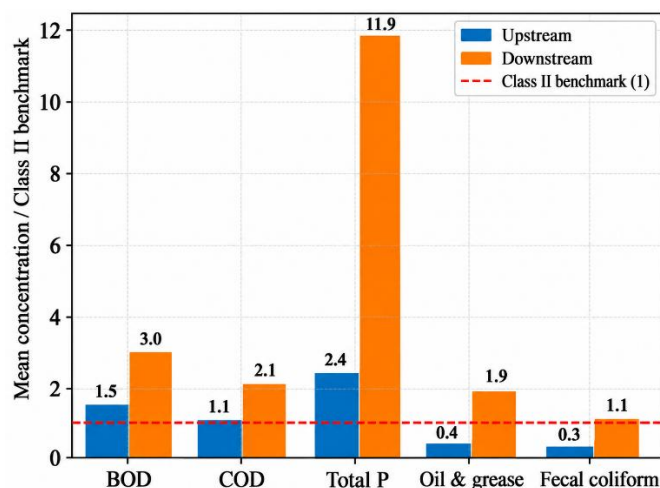


Figure 3. Upstream and Downstream Water-Quality Benchmark Exceedance Factors in the Air Bengkulu River, 2025.

The exceedance patterns shown in Figure 3 complement the concentration measurements in Table 3 by expressing pollution levels relative to their respective regulatory limits. This comparison is important because pollutants with relatively low absolute concentrations may still represent substantial regulatory exceedances. The particularly high phosphate exceedance factor indicates a significant nutrient-management concern, while repeated BOD, COD, oil-and-grease, and fecal-coliform exceedances demonstrate the presence of multiple water-quality pressures.

The simultaneous occurrence of these pollutants suggests that downstream raw-water quality was influenced by a combination of organic, nutrient, hydrocarbon-related, and microbial contamination during the monitored events. Such conditions may increase the complexity of raw-water management and require closer monitoring of source-water quality, particularly during periods of changing river discharge. From a water-supply perspective, these findings identify potential treatment challenges and support the need for coordinated pollution prevention, wastewater management, and source-water surveillance.

Nevertheless, the monitoring results should be interpreted within the limitations of the sampling design. The three monitoring campaigns demonstrate repeated exceedances on the sampled dates but do not establish year-round contamination frequency, seasonal patterns, or long-term trends. Furthermore, the study did not evaluate treatment-plant operations or finished-water quality. Therefore, the observed exceedances cannot be directly linked to changes in chemical consumption, sludge production, energy requirements, filtration efficiency, treatment yield, or drinking-water compliance. The findings instead provide

evidence of source-water pollution pressure and identify parameters requiring further investigation to support raw-water abstraction and treatment planning

3.4. Event-based pollutant transport under contrasting discharge

Event-based pollutant transport was evaluated using concurrent river-discharge and water-quality measurements collected during two monitoring campaigns in 2024. Unlike concentration-based assessments, pollutant-load calculations account for both contaminant concentration and river discharge, providing a more comprehensive indication of the mass transported through a monitoring section. This distinction is particularly important in tropical watersheds, where variations in rainfall and runoff can substantially influence pollutant transport.

During the first monitoring event on 29 February 2024, upstream discharge was $8.70 \text{ m}^3 \text{ s}^{-1}$, compared with $38.95 \text{ m}^3 \text{ s}^{-1}$ downstream. The corresponding COD concentrations were 21 and 35 mg L^{-1} , resulting in estimated daily-equivalent COD loads of 15.8 and 117.8 t day^{-1} , respectively. The substantially higher downstream COD load reflected the combined effects of increased concentration and greater river discharge. This finding demonstrates that changes in pollutant transport cannot be adequately explained by concentration differences alone.

A contrasting pattern was observed on 6 May 2024, when the reported upstream discharge reached $217.41 \text{ m}^3 \text{ s}^{-1}$, considerably exceeding the downstream discharge of $47.42 \text{ m}^3 \text{ s}^{-1}$. The estimated upstream COD load was 338.1 t day^{-1} , compared with 135.2 t day^{-1} downstream. In contrast, total suspended solids (TSS) transport was estimated at 131.5 t day^{-1} upstream and 172.1 t day^{-1} downstream. These differences illustrate the sensitivity of pollutant-load estimates to variations in both discharge and concentration.

However, the substantially higher upstream discharge recorded in May was hydrologically unusual for a direct upstream–downstream comparison. Potential explanations include differences in measurement timing, observations made during different hydrograph phases, localized runoff or tributary influences, and uncertainties associated with discharge measurements or rating relationships. Because these possibilities could not be independently verified, the observed discharge difference cannot be attributed to a specific hydrological mechanism. Consequently, the May measurements should not be interpreted as a synchronous river-reach mass balance or used to infer net pollutant removal, accumulation, or source contributions.

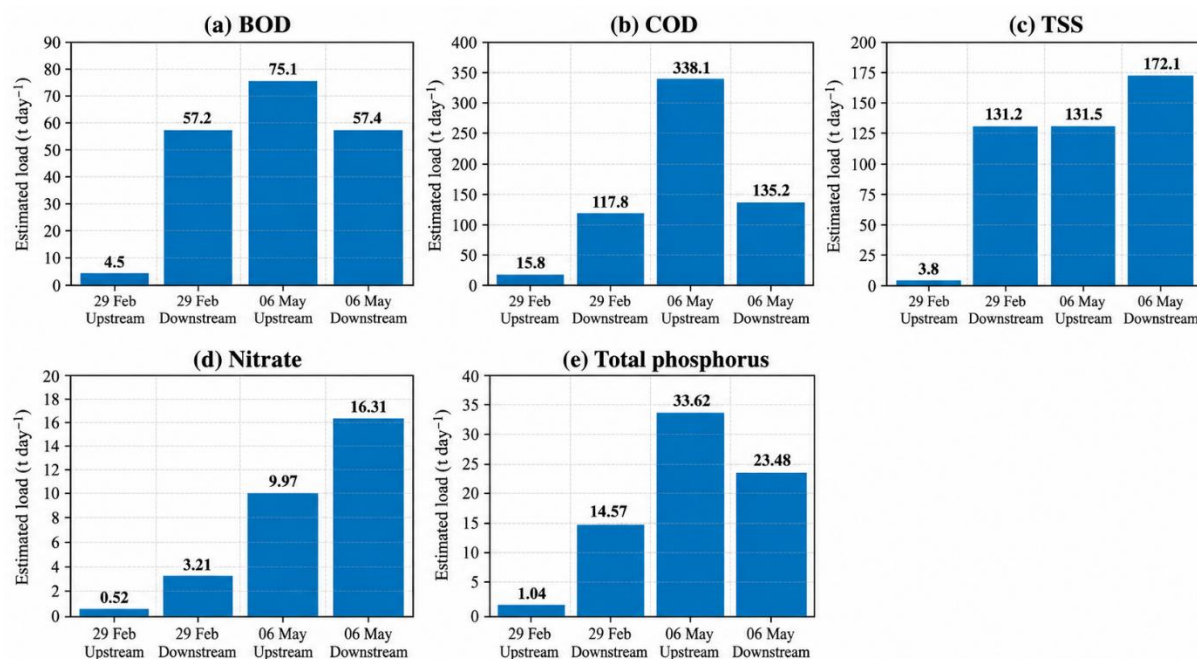
The event-specific transport estimates for BOD, COD, TSS, nitrate, and total phosphorus are summarized in Table 4. The results demonstrate substantial differences in pollutant transport between monitoring events and river sections. For example, downstream BOD transport increased from 57.2 t day^{-1} in February to 57.4 t day^{-1} in May, despite differences in discharge. Downstream TSS transport increased from 131.2 to 172.1 t day^{-1} , while total phosphorus transport increased from 14.57 to 23.48 t day^{-1} . These findings indicate that individual pollutants may exhibit different transport responses under changing hydrological conditions.

Table 4. Event-Based Pollutant Transport Estimates at Upstream and Downstream Monitoring Sections of the Air Bengkulu River, 2024.

Date	Segment	Q (m ³ /s)	BOD (t/day)	COD (t/day)	TSS (t/day)	NO ₃ (t/day)	Total P (t/day)
29 Feb 2024	Upstream	8.70	4.5	15.8	3.8	0.49	1.03
29 Feb 2024	Downstream	38.95	57.2	117.8	131.2	2.11	14.57
6 May 2024	Upstream	217.41	75.1	338.1	131.5	9.97	33.62
6 May 2024	Downstream	47.42	57.4	135.2	172.1	16.31	23.48

Note: Pollutant loads represent daily-equivalent transport estimates calculated from the discharge and concentration measured during each monitoring event. They do not represent measured daily totals, annual pollutant loads, or closed-reach mass balances.

The differences in pollutant transport are further illustrated in Figure 4, which compares upstream and downstream daily-equivalent loads for BOD, COD, TSS, nitrate, and total phosphorus during the two monitoring campaigns. The figure highlights the contrasting transport patterns among pollutants and demonstrates that higher concentrations do not necessarily correspond to greater pollutant loads when discharge conditions differ. The particularly high upstream discharge recorded in May strongly influenced the estimated COD transport, whereas downstream TSS and nitrate loads remained higher than their upstream counterparts. These results reinforce the importance of interpreting pollutant concentrations alongside hydrological conditions rather than relying on either indicator independently.

**Figure 4.** Event-Based Pollutant Transport Estimates for BOD (A), COD (B), TSS (C), Nitrate (D), and Total Phosphorus (E) During the Two 2024 Campaigns With Concurrent Concentration and Discharge Records.

Overall, the event-based assessment demonstrates that pollutant transport in the Air Bengkulu River is strongly influenced by river discharge and pollutant-specific concentration patterns. However, the limited number of monitoring events and uncertainty surrounding the May discharge measurements restrict the interpretation of spatial pollutant balances. The findings therefore provide event-specific evidence of transport variability rather than estimates of long-term pollutant export or definitive source contributions. More frequent, flow-

synchronized measurements are required to characterize pollutant transport under different hydrological conditions and support reliable pollution-management decisions.

3.5. Integrated Interpretation: Pollution as a Constraint on Effective Raw-Water Security.

The combined hydrological, service-delivery, and water-quality findings provide a more comprehensive understanding of raw-water security in the Air Bengkulu Watershed. Although dependable river flow substantially exceeded normative domestic water demand, this hydrological potential did not necessarily translate into directly usable or accessible water. Previous global assessments have demonstrated that pollution can increase exposure to water scarcity even in regions with relatively abundant freshwater resources [1, 2]. In the present study, repeated downstream water-quality exceedances during the three monitoring campaigns indicated that pollution represented an additional concern for raw-water management alongside hydrological availability and water-service delivery.

The downstream contamination pattern involved organic pollutants, nutrients, oil and grease, and fecal indicators, suggesting that multiple pollution pathways should be investigated. Elevated BOD and COD concentrations indicate the need to examine domestic wastewater, commercial discharges, and urban drainage. High total phosphorus concentrations support further investigation of nutrient-rich wastewater, agricultural runoff, and erosion-related inputs. Oil-and-grease exceedances warrant surveillance of workshops, transport-related runoff, and commercial drainage, while fecal-coliform contamination highlights potential sanitation-related pathways, including septic leakage, sewer overflows, and contaminated surface runoff. However, these associations represent potential pollution sources rather than confirmed source contributions. Previous studies have similarly demonstrated that nutrient and microbial contamination in river systems can reflect interactions among land use, hydrology, wastewater discharge, agricultural activities, and urban runoff [4–10, 17–19].

Land-use changes within the Air Bengkulu Watershed provide additional context for understanding these pollution pressures. Previous investigations have documented forest loss, expansion of settlements and productive land, changes in runoff characteristics, and altered hydrological behavior [31–35]. Recent research on the Bengkulu River has also identified spatial and temporal variations in nutrient concentrations across the river–estuary system [43]. Together with evidence that point and diffuse pollution sources produce different contaminant mixtures and environmental risks [12–16], these findings support the possibility of combined pressures from domestic wastewater, agricultural and plantation runoff, urban drainage, disturbed land, mining-related runoff, and commercial activities. Nevertheless, the present dataset does not quantify the contribution of individual sources, and further source apportionment is required before definitive attribution can be established.

From a water-supply perspective, these findings demonstrate that source-water protection, treatment preparedness, and service-delivery improvements should be considered complementary management priorities. Pollution control can improve source-water conditions but does not directly establish household service coverage or distribution efficiency. Conversely, expanding water-supply infrastructure without protecting raw-water sources may increase exposure to fluctuating water quality and associated treatment requirements. Therefore, raw-water security should be evaluated across the entire source-to-service chain, including pollution sources, river reaches, intake locations, treatment facilities, storage systems, and distribution networks. Each component requires specific monitoring indicators to

distinguish source-water conditions from actual treatment performance and household service outcomes.

3.6. Wastewater, Runoff, and Source-Control Priorities.

The observed water-quality exceedances provide a basis for developing risk-based pollution-management priorities in the Air Bengkulu Watershed. Although the available data do not establish definitive source contributions, the combination of organic, nutrient, hydrocarbon-related, and microbial contamination indicates the need for coordinated wastewater and runoff management. First, pollution-control measures should target potential sources associated with the observed indicator patterns. Repeated BOD and COD exceedances support investigations of untreated domestic wastewater, septic leakage, commercial organic discharges, and drainage outfalls. Elevated total phosphorus concentrations indicate the importance of managing nutrient inputs from sanitation systems, agricultural and plantation activities, erosion, and sediment mobilization. Oil-and-grease contamination warrants inspection of workshops, vehicle-service facilities, commercial premises, road runoff, and drainage systems receiving hydrocarbon residues. Similarly, recurring fecal-coliform exceedances highlight the need for sanitation improvements, septic-system maintenance, and microbial contamination surveillance. These measures should be implemented as risk-based investigation and control priorities rather than conclusions about confirmed pollution sources.

Second, water utilities should strengthen intake monitoring and operational preparedness in response to changing source-water conditions. Flow-synchronized monitoring should combine river stage and discharge measurements with rapidly measurable water-quality indicators, including turbidity, conductivity, pH, dissolved oxygen, and selected organic pollution indicators. These observations should be supported by laboratory analyses to confirm regulatory exceedances and identify changes in pollutant concentrations. Sudden deterioration in source-water quality could trigger intensified intake sampling, operational assessments, coagulant-demand testing, and contingency planning. Previous studies have demonstrated that rainfall and hydrological variability can substantially influence raw-water quality and treatment requirements [20, 21]. However, the actual operational responses of treatment facilities in Bengkulu must be established using plant-specific records rather than inferred directly from river-water measurements.

Third, the household piped-service realization ratio of 38.0% should be used as an indicator for further investigation of water-supply performance rather than as a measure of household coverage. A comprehensive utility water balance should distinguish water production, treatment losses, storage, pumping, distribution pressure, physical leakage, commercial losses, customer connections, service continuity, and non-piped household water use. Such information would allow the relative contributions of infrastructure limitations, treatment capacity, distribution efficiency, and source-water interruptions to be evaluated more accurately.

Fourth, preventive watershed management should address potential pollution pathways before contaminants reach raw-water intake locations. Priority measures include riparian-zone protection, erosion and sediment control, rehabilitation of disturbed or mined areas where applicable, agricultural nutrient management, improved stormwater drainage, wastewater containment, and inspection of high-risk commercial discharges. These interventions should be supported by georeferenced pollution-source inventories and targeted tributary and outfall

monitoring. Previous studies have demonstrated that catchment characteristics, land use, and runoff conditions can strongly influence nutrient export and event-based pollutant loading [5–10, 23].

Finally, the watershed monitoring program should integrate water quality, discharge, and pollution-source information within a coordinated decision-support system. Conventional concentration-based monitoring cannot independently quantify pollutant mass transport, while discharge measurements alone provide limited information about source-water suitability. A more effective monitoring strategy would combine fixed upstream, intake, and downstream stations with synchronous discharge and water-quality measurements, tributary and outfall observations, and targeted sampling during low-flow, high-flow, and rainfall events. Such an approach would support early warning, pollution-source investigation, regulatory enforcement, and evaluation of pollution-control effectiveness [24, 25, 27].

These management priorities are integrated in Figure 5, which presents a proposed framework linking watershed pollution control, hydrological monitoring, source-water assessment, treatment preparedness, and service-delivery evaluation. The framework emphasizes that reliable raw-water security requires coordinated management across the entire source-to-service chain rather than isolated improvements in water quantity, treatment infrastructure, or distribution capacity.

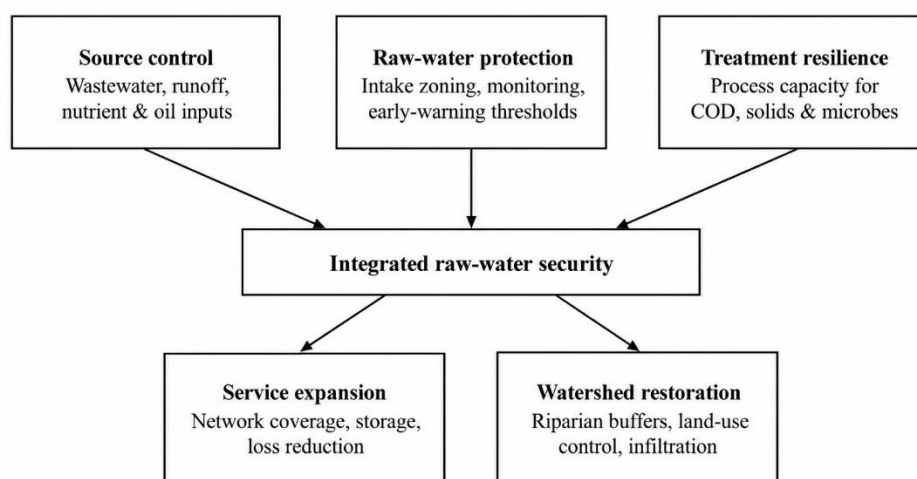


Figure 5. Integrated Management Framework for Converting Hydrological Potential Into Reliable, Treatable, and Accessible Raw-Water Supply.

3.7. Potential Treatment Implications and Source-to-Service Integration.

The observed water-quality conditions have potential implications for raw-water treatment and water-supply planning. Previous studies have demonstrated that source-water deterioration can increase operational challenges for drinking-water treatment systems, particularly under variable rainfall and hydrological conditions [20–22]. However, the present study did not include treatment-plant operating records, and therefore, the identified treatment implications should be interpreted as potential operational concerns rather than measured changes in treatment performance.

The recurring downstream exceedances of organic, nutrient, oil-and-grease, and microbial indicators highlight the importance of incorporating source-water quality into intake management and treatment preparedness. Elevated organic pollution may require closer

monitoring of treatment-relevant water-quality characteristics, while nutrient and microbial contamination can indicate additional source-water management concerns. Nevertheless, determining actual treatment requirements would require information on raw-water intake concentrations, treatment processes, chemical consumption, operational efficiency, and finished-water quality.

Recent research provides further support for integrating source-water protection with treatment and distribution management. Basin-wide assessments have shown that anthropogenic pollution pressures may increase downstream [26], while source-to-intake transport modelling can improve understanding of pollutant movement toward abstraction points [28]. Runoff pretreatment and reservoir-based interventions may also reduce pollution pressure before conventional treatment [29]. Furthermore, source-to-tap investigations have demonstrated that water-quality characteristics can change throughout treatment and distribution processes [30].

For the Air Bengkulu Watershed, these findings support a layered management strategy that combines pollution prevention, flow-synchronized intake monitoring, treatment-plant operational assessment, and distribution-system evaluation. Such integration would allow water utilities and environmental authorities to distinguish between hydrological availability, quality-related constraints, treatment capacity, and actual service delivery. The proposed source-to-service framework therefore provides a basis for improving raw-water planning while avoiding unsupported assumptions about treatment performance or household water access.

3.8. Study Limitations and Future Research Priorities.

Several limitations should be considered when interpreting the findings. First, the Q90 value was obtained from a previously published dependable-flow assessment rather than recalculated from the original hydrological time series [35]. The normative domestic water-demand coefficient of 120 L capita⁻¹ day⁻¹ was adopted as a planning benchmark [38] and did not represent measured household consumption in Bengkulu City. Similarly, recorded household piped-water delivery did not directly indicate actual consumption, household coverage, or service reliability. Information on environmental-flow requirements, licensed abstractions, sectoral water withdrawals, treatment capacity, non-revenue water, network coverage, and service continuity was unavailable. Consequently, the HAR of 19.65 and household service-realization ratio of 38.0% should be interpreted strictly as diagnostic indicators rather than direct measures of usable raw-water availability or household water-access coverage.

Second, the water-quality dataset was limited to three paired monitoring campaigns in 2025. Although repeated regulatory exceedances were observed during these events, the sampling frequency was insufficient to establish annual exceedance rates, seasonal variability, first-flush effects, or short-term pollutant peaks. Similarly, pollutant transport was estimated using only two monitoring campaigns in 2024 with concurrent concentration and discharge records. The unusually high upstream discharge recorded on 6 May 2024 introduced additional uncertainty regarding the spatial interpretation of pollutant loads. Because measurement timing, hydrograph conditions, and potential discharge uncertainties could not be resolved, the event-based estimates should not be interpreted as closed-reach pollutant balances.

Third, the study did not perform quantitative pollution-source apportionment. Therefore, domestic wastewater, agricultural runoff, urban drainage, mining-related runoff, and

commercial activities were identified only as potential pollution pathways. Their relative contributions remain unknown. The absence of treatment-plant operating data also prevented direct evaluation of how source-water pollution affected treatment efficiency, operational costs, or finished-water quality.

Future research should integrate continuous or daily discharge measurements, environmental-flow requirements, sectoral water-use records, treatment-plant operating data, non-revenue water estimates, household service indicators, and flow-synchronized water-quality observations. Monitoring should cover wet-season, dry-season, first-flush, and high-flow conditions to improve temporal representativeness and quantify pollutant transport variability.

Advanced source-identification methods, including inverse modelling, multivariate receptor analysis, microbial source tracking, and hybrid source-apportionment frameworks, could be applied to identify dominant pollution pathways [15–18, 27]. With sufficient monitoring data, calibrated QUAL2K or comparable water-quality models could also be integrated with source-to-service system dynamics to evaluate the relationships among hydrological potential, quality-constrained water availability, treatment capacity, delivered supply, demand, service coverage, and reliability. Such developments would support more comprehensive and operationally relevant assessments of raw-water security in tropical urban watersheds.

4. Conclusions

This study demonstrated that the Air Bengkulu Watershed has substantial dependable-flow potential relative to normative domestic water demand, although hydrological availability alone does not ensure raw-water security. The hydrological availability ratio (HAR) of 19.65 represents a diagnostic comparison between 90% dependable flow (Q90) and normative domestic demand rather than an estimate of abstractable water supply. Similarly, the household piped-service realization ratio of 38.0% reflects recorded household water delivery relative to the normative demand benchmark and should not be interpreted as household service coverage, actual consumption, or total water availability. Water-quality monitoring during three campaigns in 2025 revealed repeated downstream exceedances of Class II benchmarks for organic pollutants, nutrients, oil and grease, and fecal contamination indicators, highlighting recurring source-water quality concerns during the monitored events. The findings emphasize the importance of integrating wastewater and runoff control, flow-synchronized water-quality monitoring, intake surveillance, treatment preparedness, and utility water-balance assessments. The observed pollution indicators provide a basis for prioritizing investigations of potential domestic, agricultural, urban, commercial, and disturbed-land pollution sources, although their individual contributions remain unquantified. Event-based pollutant-load estimates further demonstrated that discharge must be considered alongside concentration to accurately interpret pollutant transport. Overall, the proposed source-to-service framework provides an integrated approach to assessing hydrological potential, pollution constraints, and water-service delivery. Future research should quantify seasonal water-quality variability, pollutant-source contributions, environmental-flow requirements, treatment capacity, operational performance, non-revenue water, household coverage, and service continuity. Integrating these measurements with calibrated water-quality and system-dynamics models would support more reliable assessments of usable water availability and the development of effective watershed-

management strategies. Such an approach could strengthen raw-water security by connecting pollution prevention, treatment preparedness, and service delivery without assuming that all dependable river flow is directly available for abstraction and distribution.

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Author Contribution

R.A.: Conceptualization, Methodology, Data Curation, Formal Analysis, Investigation, Visualization, Writing – Original Draft. Y.H.B.: Conceptualization, Methodology, Validation, Supervision, Writing – Review & Editing. W.A.: Methodology, Validation, Formal Analysis, Interpretation of Results, Supervision, Writing – Review & Editing. K.A.: Validation, Data Interpretation, Supervision, Writing – Review & Editing. All authors have read and approved the final manuscript. For clarity, author roles correspond to Riang Adeko (R.A.), Yudhi Harini Bertham (Y.H.B.), Wahyudi Arianto (W.A.), and Khairul Amri (K.A.).

Competing Interest

No conflict of interest was reported by all authors.

References

- [1] Wang, M.; Bodirsky, B.L.; Rijnveld, R.; Beier, F.; Bak, M.P.; et al. (2024). A triple increase in global river basins with water scarcity due to future pollution. *Nature Communications*, 15, 880. <https://doi.org/10.1038/s41467-024-44947-3>.
- [2] Baccour, S.; Goelema, G.; Kahil, T.; Albiac, J.; van Vliet, M.T.H.; et al. (2024). Water quality management could halve future water scarcity cost-effectively in the Pearl River Basin. *Nature Communications*, 15, 5669. <https://doi.org/10.1038/s41467-024-49929-z>.
- [3] Li, Y.; Wang, H.; Deng, Y.; Liang, D.; Li, Y.; et al. (2023). Applying water environment capacity to assess the non-point source pollution risks in watersheds. *Water Research*, 240, 120092. <https://doi.org/10.1016/j.watres.2023.120092>.
- [4] Wu, H.; Jiao, X.; Wang, Y.; Wang, M.; Zhou, J.; et al. (2024). Influence of climate and land use on watershed anthropogenic phosphorus inputs and riverine phosphorus export dynamics: A global analysis. *Science of the Total Environment*, 933, 172991. <https://doi.org/10.1016/j.scitotenv.2024.172991>.
- [5] Crowson, M.; Pettorelli, N.; Isaac, N.J.B.; Norris, K.; Wade, A.J. (2024). Quantifying the relative importance of agricultural land use as a predictor of catchment nitrogen and phosphorus concentrations. *Science of the Total Environment*, 954, 176589. <https://doi.org/10.1016/j.scitotenv.2024.176589>.
- [6] Chan, P.L.R.; Arhonditsis, G.B.; Thompson, K.A.; Eimers, M.C. (2024). A regional examination of the footprint of agriculture and urban cover on stream water quality. *Science of the Total Environment*, 945, 174157. <https://doi.org/10.1016/j.scitotenv.2024.174157>.

- [7] McDowell, R.W.; McNeill, S.J.; Drewry, J.J.; Law, R.; Stevenson, B. (2024). Difficulties in using land use pressure and soil quality indicators to predict water quality. *Science of the Total Environment*, 935, 173445. <https://doi.org/10.1016/j.scitotenv.2024.173445>.
- [8] Nepal, D.; Parajuli, P.B.; Ouyang, Y.; To, S.D.F.; Wijewardane, N. (2023). Assessing hydrological and water quality responses to dynamic landuse change at watershed scale in Mississippi. *Journal of Hydrology*, 625, 129983. <https://doi.org/10.1016/j.jhydrol.2023.129983>.
- [9] Yu, S.; Meng, C.; Li, Y.; Liu, H.; Xia, Y.; et al. (2024). The phosphorus export coefficients variability of specific land-use and the threshold response relationship with watershed characteristics in a subtropical hilly region. *Science of the Total Environment*, 957, 177635. <https://doi.org/10.1016/j.scitotenv.2024.177635>.
- [10] Li, Y.; Mi, W.; Ji, L.; He, Q.; Yang, P.; et al. (2023). Urbanization and agriculture intensification jointly enlarge the spatial inequality of river water quality. *Science of the Total Environment*, 878, 162559. <https://doi.org/10.1016/j.scitotenv.2023.162559>.
- [11] Salomao, G.N.; Dall'Agnol, R.; Sahoo, P.K.; de Almeida, G.S.; Amarante, R.T.; et al. (2023). Changes in the surface water quality of a tropical watershed in the southeastern Amazon due to the environmental impacts of artisanal mining. *Environmental Pollution*, 329, 121595. <https://doi.org/10.1016/j.envpol.2023.121595>.
- [12] Liu, Y.; Su, B.; Mu, H.; Zhang, Y.; Chen, L.; et al. (2023). Effects of point and nonpoint source pollution on urban rivers: From the perspective of pollutant composition and toxicity. *Journal of Hazardous Materials*, 460, 132441. <https://doi.org/10.1016/j.jhazmat.2023.132441>.
- [13] Wang, W.; Zhang, F.; Zhao, Q.; Liu, C.; Jim, C.Y.; et al. (2023). Determining the main contributing factors to nutrient concentration in rivers in arid northwest China using partial least squares structural equation modeling. *Journal of Environmental Management*, 343, 118249. <https://doi.org/10.1016/j.jenvman.2023.118249>.
- [14] Li, X.; Xu, Y.J.; Ni, M.; Wang, C.; Li, S. (2023). Riverine nitrate source and transformation as affected by land use and land cover. *Environmental Research*, 222, 115380. <https://doi.org/10.1016/j.envres.2023.115380>.
- [15] Chrapkiewicz, K.; Lipp, A.G.; Barron, L.P.; Barnes, R.; Roberts, G.G. (2024). Apportioning sources of chemicals of emerging concern along an urban river with inverse modelling. *Science of the Total Environment*, 933, 172827. <https://doi.org/10.1016/j.scitotenv.2024.172827>.
- [16] Soetan, O.; Nie, J.; Polius, K.; Feng, H. (2024). Application of time series and multivariate statistical models for water quality assessment and pollution source apportionment in an urban river, New Jersey, USA. *Environmental Science and Pollution Research*, 31, 61643–61659. <https://doi.org/10.1007/s11356-024-35330-2>.
- [17] Friedman, S.D.; Cooper, E.; Blackwell, A.; Elliott, M.A.; Weinstein, M.; et al. (2024). A multi-tiered approach to assess fecal pollution in an urban watershed: Bacterial and viral indicators and sediment microbial communities. *Science of the Total Environment*, 945, 174141. <https://doi.org/10.1016/j.scitotenv.2024.174141>.
- [18] Tian, Y.; Han, Z.; Su, D.; Luan, X.; Yu, L.; et al. (2024). Assessing impacts of municipal wastewater treatment plant upgrades on bacterial hazard contributions to the receiving urban river using SourceTracker. *Environmental Pollution*, 342, 123075. <https://doi.org/10.1016/j.envpol.2023.123075>.
- [19] Xiao, Z.; Qin, Y.; Han, L.; Liu, Y.; Wang, Z.; et al. (2024). Effects of wastewater treatment plant effluent on microbial risks of pathogens and their antibiotic resistance in the receiving river. *Environmental Pollution*, 345, 123461. <https://doi.org/10.1016/j.envpol.2024.123461>.
- [20] Delpla, I.; Bouchard, C.; Dorea, C.; Rodriguez, M.J. (2023). Assessment of rain event effects on source water quality degradation and subsequent water treatment operations. *Science of the Total Environment*, 866, 161085. <https://doi.org/10.1016/j.scitotenv.2022.161085>.

- [21] Ortiz-Lopez, C.; Bouchard, C.; Rodriguez, M.J. (2024). Ensemble machine learning using hydrometeorological information to improve modeling of quality parameter of raw water supplying treatment plants. *Journal of Environmental Management*, 362, 121378. <https://doi.org/10.1016/j.jenvman.2024.121378>.
- [22] Compaore, S.M.C.; Delpla, I.; Behmel, S.; Rodriguez, M. (2024). Review of climate change and drinking water supply systems: Employee perspectives and potential tools for adaptation. *Environmental Reviews*, 32, 68–90. <https://doi.org/10.1139/er-2023-0052>.
- [23] Ochoa, L.; Chan, J.; Auguste, C.; Arbuckle-Keil, G.; Fahrenfeld, N.L. (2024). Stormwater runoff microplastics: Polymer types, particle size, and factors controlling loading rates. *Science of the Total Environment*, 929, 172485. <https://doi.org/10.1016/j.scitotenv.2024.172485>.
- [24] Shelton, S.A.; Kaushal, S.S.; Mayer, P.M.; Shatkay, R.R.; Rippey, M.A.; et al. (2024). Salty chemical cocktails as water quality signatures: Longitudinal trends and breakpoints along different U.S. streams. *Science of the Total Environment*, 930, 172777. <https://doi.org/10.1016/j.scitotenv.2024.172777>.
- [25] Jiang, J.; Men, Y.; Pang, T.; Tang, S.; Hou, Z.; et al. (2023). An integrated supervision framework to safeguard the urban river water quality supported by ICT and models. *Journal of Environmental Management*, 331, 117245. <https://doi.org/10.1016/j.jenvman.2023.117245>.
- [26] Zhang, K.; Chang, S.; Tu, X.; Wang, E.; Yu, Y.; et al. (2024). Heavy metals in centralized drinking water sources of the Yangtze River: A comprehensive study from a basin-wide perspective. *Journal of Hazardous Materials*, 469, 133936. <https://doi.org/10.1016/j.jhazmat.2024.133936>.
- [27] Zhang, Q.; Guo, X.; Sun, W.; Chang, Z.; Liang, J.; et al. (2025). Towards holistic river pollution source apportionment: Multi-faceted framework across scenarios, media, pollutants, and sources. *Environmental Research*, 286, 122998. <https://doi.org/10.1016/j.envres.2025.122998>.
- [28] Bhide, S.V.; Grant, S.B.; Benettin, P.; Rippey, M.A.; Monofy, A.; et al. (2026). Transit times link pollution sources to drinking water quality in a One Water system. *Water Research*, 288, 124652. <https://doi.org/10.1016/j.watres.2025.124652>.
- [29] Li, N.; Hu, W.; Gao, Y.; Si, F.; Wen, C.; et al. (2026). Assessing source water reservoirs as pre-treatment units for simultaneous control of autochthonous and runoff pollution through artificial mixing and aeration technology. *Water Research*, 290, 125029. <https://doi.org/10.1016/j.watres.2025.125029>.
- [30] Gabrielli, M.; Pulcini, F.; Barbesti, G.; Antonelli, M. (2024). Source to tap investigation of natural organic matter in non-disinfected drinking water distribution systems. *Environmental Science: Water Research & Technology*, 10, 128–143. <https://doi.org/10.1039/D3EW00280B>.
- [31] Barchia, M.F.; Sulisty, B.; Hindarto, K.S.; Suhartoyo, H. (2020). Assessment of Air Bengkulu (Indonesia) watershed based on agroecosystem landscape quality and sustainable land use plan. *Biodiversitas Journal of Biological Diversity*, 21. <https://doi.org/10.13057/biodiv/d211150>.
- [32] Izzatuddinillah, I. (2023). Analysis of land use and spatial patterns based on flow regime coefficients (FRC) in DAS Air Bengkulu. *Jurnal Ilmu Tanah dan Lingkungan*, 25, 56–63. <https://doi.org/10.29244/jitl.25.2.56-63>.
- [33] Saraswati, G.S.; Asdak, C.; Joy, B. (2025). Karakteristik Daerah Aliran Sungai (DAS) Air Bengkulu dan perubahan penggunaan lahannya dalam kaitannya dengan kejadian banjir. *Jurnal Ilmu Lingkungan*, 23, 915–922. <https://doi.org/10.14710/jil.23.4.915-922>.
- [34] Sulisty, B.; Adiprasetyo, T.; Murcitra, B.G.; Purwadi, A.J.; Listyaningrum, N. (2024). Runoff coefficient in the Air Bengkulu Watershed and the evaluation of the existing spatial planning. *Indonesian Journal of Geography*, 56. <https://doi.org/10.22146/ijg.91397>.
- [35] Khalik, I.; Sapei, A.; Hariyadi, S.; Anggraeni, E. (2025). Analysis of dependable discharge and management policy of Bengkulu Watershed for raw water availability in Bengkulu City. *Jurnal Penelitian Pengelolaan Daerah Aliran Sungai*, 9, 79–104. <https://doi.org/10.59465/jppdas.2025.9.1.79-104>.

- [36] Dinas Kependudukan dan Pencatatan Sipil Kota Bengkulu (2025). Data Penduduk Kota Bengkulu Semester II Tahun 2024; Disdukcapil Kota Bengkulu: Bengkulu, Indonesia.
- [37] Badan Pusat Statistik Kota Bengkulu (2025). Kota Bengkulu Dalam Angka 2025; BPS Kota Bengkulu: Bengkulu, Indonesia.
- [38] Badan Standardisasi Nasional (2015). SNI 6728.1:2015 Penyusunan Neraca Sumber Daya – Bagian 1: Sumber Daya Air Spasial; BSN: Jakarta, Indonesia.
- [39] Pemerintah Provinsi Bengkulu (2005). Peraturan Daerah Provinsi Bengkulu Nomor 6 Tahun 2005 tentang Baku Mutu Air dan Kelas Air Sungai; Pemerintah Provinsi Bengkulu: Bengkulu, Indonesia.
- [40] UPTD Laboratorium Lingkungan Kota Bengkulu (2025). Laporan Hasil Uji Air Bengkulu Hulu dan Hilir, Sampling 30 April 2025; Dinas Lingkungan Hidup Kota Bengkulu: Bengkulu, Indonesia.
- [41] UPTD Laboratorium Lingkungan Kota Bengkulu (2025). Laporan Hasil Uji Air Bengkulu Hulu dan Hilir, Sampling 10 July 2025; Dinas Lingkungan Hidup Kota Bengkulu: Bengkulu, Indonesia.
- [42] UPTD Laboratorium Lingkungan Kota Bengkulu (2025). Laporan Hasil Uji Air Bengkulu Hulu dan Hilir, Sampling 29 October 2025; Dinas Lingkungan Hidup Kota Bengkulu: Bengkulu, Indonesia.
- [43] Wiwit, W.; Ikhsani, I.Y.; Nurhamidah, N.; Oktiarni, D.; Wong, K.H. (2025). Assessment of macronutrient dynamics in a tropical watershed: A study from Bengkulu River and Estuary Indonesia. *Jurnal Kimia Valensi*, 11, 41–49. <https://doi.org/10.15408/jkv.v11i1.42477>.



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