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Integrating physicochemical, biological, sediment, and riparian indicators in the upstream segment of the Upper Konto sub-watershed, Indonesia

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ABSTRACT

River-health assessments in tropical headwater systems often rely on physicochemical parameters, which may not fully capture cumulative ecological degradation under strong seasonal hydrological variability. This study evaluated river condition in the upstream segment of the Upper Konto sub-watershed, Indonesia, using an integrated ecohydraulic framework combining physicochemical indicators, biological responses, sediment nutrient dynamics, and riparian vegetation characteristics. Water quality was assessed using the pollution index (PI), while ecological condition was evaluated through the family biotic index (FBI) based on macroinvertebrate assemblages. Sediment nutrient concentrations, hydrological variability, substrate characteristics, and riparian vegetation conditions were analyzed during both dry and rainy seasons across nine sampling stations. The results demonstrated clear seasonal ecohydraulic effects. River discharge increased from 0.038–5.688 m^3/s during the dry season to 0.23–13.404 m^3/s in the rainy season, while flow velocity increased from 0.12–0.82 m/s to 0.46–1.02 m/s. Although PI classified most sites as lightly to moderately polluted, FBI values indicated fair to very poor ecological conditions, particularly during the rainy season, revealing a marked divergence between physicochemical and biological assessments. Macroinvertebrate communities were dominated by pollution-tolerant taxa, with sensitive taxa absent, indicating persistent ecological stress associated with organic pollution, sediment disturbance, and habitat degradation. Sandy sediments enriched with nitrogen, phosphorus, and potassium acted as nutrient sinks contributing to long-term ecological pressure. The study demonstrates that river condition in tropical agricultural headwaters is more accurately explained by integrating physicochemical, biological, sedimentary, and riparian indicators than by conventional water-quality assessment alone. The main limitation of the study is the spatially restricted sampling design within a single tropical watershed. The findings support broader application of ecohydraulic bioassessment in watershed monitoring and river management. The originality of this work lies in linking seasonal hydrological variability, sediment nutrient enrichment, riparian buffering, and biological degradation within a unified assessment framework for tropical headwater rivers.

Keywords: ecohydraulic assessment, pollution index, family biotic index, macroinvertebrates, riparian vegetation.

INTRODUCTION

Programs of monitoring and restoration should consider that rivers are dynamic socio-ecological systems, where their condition is strongly mediated by interactions among hydrology, sediment dynamics, habitat structure, and land-use pressures. Diffuse loading of nutrients, livestock waste, domestic discharges, and sediment transport from runoff can rapidly degrade water quality and ecological integrity in agricultural headwaters, with downstream effects throughout a river network. Long-term perspectives also show that agricultural and urban pressures impact river condition not only via changes in physicochemical properties but also due to community reconstruction and alteration of pollutant pathways, reinforcing the idea that river degradation should be viewed as cumulative rather than episodic (Cieplok et al., 2025; Tao and Liu, 2024; Soetan et al., 2024).

A second body of research emphasizes that riparian zones serve as the interface through which terrestrial pressures are transmitted to aquatic systems. Riparian vegetation helps regulate sediment and nutrient fluxes, stabilizes banks, and provides a variety of ecosystem services, often delivering ecological benefits that are disproportionate to its spatial extent (Riis et al., 2020). But riparian integrity is increasingly being compromised by land-use change, pollution, and hydromorphological alteration, although many assessment frameworks continue to underplay its functional role in river processes (González del Tánago et al., 2021). While empirical studies across geographical regions consistently demonstrate the positive correlation between riparian condition and water quality, changes in the structure (e.g., terrestrial vegetation), spatial composition (e.g., coverage), or utilization of riverfronts have frequently aggravated nutrient transfer/accumulation and pollutant influx along river corridors (Granitto et al., 2025; Wang et al., 2025; Zou et al., 2025; Ji et al., 2024).

A third set of studies has examined the river-health assessment itself and has highlighted an important methodological limitation. While physicochemical parameters remain the primary basis for assessing water quality, they reflect conditions at a specific, integrated time of sampling and may not capture cumulative ecological disturbance. In contrast, benthic macroinvertebrates reflect longer-term responses to pollution, habitat degradation, substrate condition, and flow variability, thereby providing more reliable measures of ecological impairment (Sripanya et al., 2023; Bilalli et al., 2022; Ilham et al., 2022). Recent bioassessment studies further confirm that the presence, absence, richness, and abundance of pollution-sensitive and pollution-tolerant macroinvertebrate taxa can reveal ecological degradation that is not fully detected through water-column measurements alone (Ilham et al., 2022; Bilalli et al., 2022). Concomitantly, ecohydraulic studies have demonstrated that hydrodynamic variability dominates habitat availability, benthic retention time, and ecological flow requirements; the physicochemical status, biological response, sediment characteristics, and hydromorphological regulators need to be interpreted as interacting components instead of separate aspects of river condition (Sedighkia and Datta, 2023; Vagenas et al., 2024; Woś and Książek, 2022).

Notwithstanding these advancements, integrated assessments that simultaneously integrate physicochemical status, biological response, sediment nutrient dynamics, and riparian functions remain few and far between in tropical highland headwaters. This limitation is significant because the co-occurrence of seasonal discharge variation, nutrient-enriched sediments, riparian disturbance, and biotic stress is commonplace in these systems, yet these processes are still evaluated independently. Consequently, traditional assessment may lose sight of the integrated ways by which hydrology, habitat, sediment, and pollution combine to drive river health.

Despite advances in individual domains of river assessment, there remains a critical gap in studies that jointly integrate physicochemical indicators, biological responses, sediment nutrient dynamics, and riparian vegetation structure within a unified analytical framework, particularly in tropical highland headwater systems. This limitation is important because these systems are typically characterized by strong seasonal hydrological variability, intensive agricultural pressure, and coupled sediment–nutrient–biota interactions, yet are still commonly assessed using disconnected or single-domain approaches. As a result, current river-health evaluations may fail to capture the cumulative and interacting effects of flow variability, habitat alteration, sediment enrichment, and biological stress on ecosystem condition. This leads to inconsistent or incomplete interpretation of ecological status when relying on either physicochemical or biological indicators alone.

Focusing on the Upper Konto sub-watershed (Indonesia), a tropical agricultural headwater system supplying the Selorejo Reservoir, this study addresses this gap by developing an integrated ecohydraulic assessment framework. The system is characterized by pronounced seasonal discharge variability, nutrient-enriched sediments, altered riparian zones, and macroinvertebrate assemblages under anthropogenic stress.

The main objective of this study is to determine how river ecological condition is shaped by the combined influence of physicochemical water quality (PI), biological responses (FBI), sediment nutrient characteristics, and riparian vegetation under seasonal hydrological variability. The central hypothesis is that biological indicators provide a more integrative and temporally stable representation of ecological degradation than physicochemical parameters alone, and that river health in tropical headwaters is best explained by the interaction between hydrological variability, sediment processes, and riparian buffering rather than by any single indicator.

MATERIALS AND METHODS

The upstream segment of the Upper Konto sub-watershed is located in Pujon District, Malang Regency, East Java, Indonesia (±1,100 m a.s.l.), and was selected as the upstream segment sub-watershed because it depicts the headwater zone of the Konto river, which drains into Selorejo reservoir as a major inflow that is affected by extensive agricultural and livestock cultivation. The sub-watershed area is 192.72 km² with about 20 km of main channel length, and the study reach extends for ±12.3 km (from springs on Mount Anjasmoro and Mount Argowayang) to Grojogan Sewu waterfall. This reach was chosen because it represents an extremely relevant site for evaluating the interplay among land-use pressure, ecohydraulic processes, and water-sediment quality in a key upstream system (Figure 1). Water and sediment sampling sites are illustrated in Figure 2.

The study used a range of instruments and supporting tools to measure water quality, collect sediment samples, and conduct laboratory analyses. Water quality parameters were measured directly in the field using a Horiba U-50 multiparameter analyzer, which records temperature, turbidity, dissolved oxygen (DO), conductivity, pH, oxidation–reduction potential (ORP), and water depth. The instrument is also equipped with an integrated GPS to record the geographic coordinates of each sampling point. Nitrate and ammonia concentrations were also measured on site using the LAQUAtwin NO_3 Nitrate Test Kit and the Hydrion AM-40 Ammonia Test Kit, respectively. Suspended sediment samples were collected using a USDH-48 sampler, which is designed for use at water depths of less than 2 m. Sediment gradation was analyzed using a sieve shaker, which separates sediment particles through a series of layered sieves with different mesh sizes, allowing sediment fractions to be classified at each sampling point. Additional supporting tools included a shovel, magnifying glass, measuring tape, alcohol sprayer, ice box, grab sampler, wooden stakes, sample bottles, oven, digital balance, weighing scale, glass funnel, beaker, Erlenmeyer flask, measuring cylinder, filter paper, and current meter. Together, these instruments supported field sampling, sample handling, and laboratory analysis, ensuring that the required physical, chemical, and sediment data were collected systematically. Figure 3 presents several instruments used in the study, while Figure 4 illustrates field data collection activities and laboratory testing procedures.

Water quality analysis was conducted using the pollution index method, the aquatic ecological condition was assessed using the family biotic index (FBI) method. Sediment characteristics were analyzed to determine grain size distribution, based on the SNI ASTM C136:2012 standard.

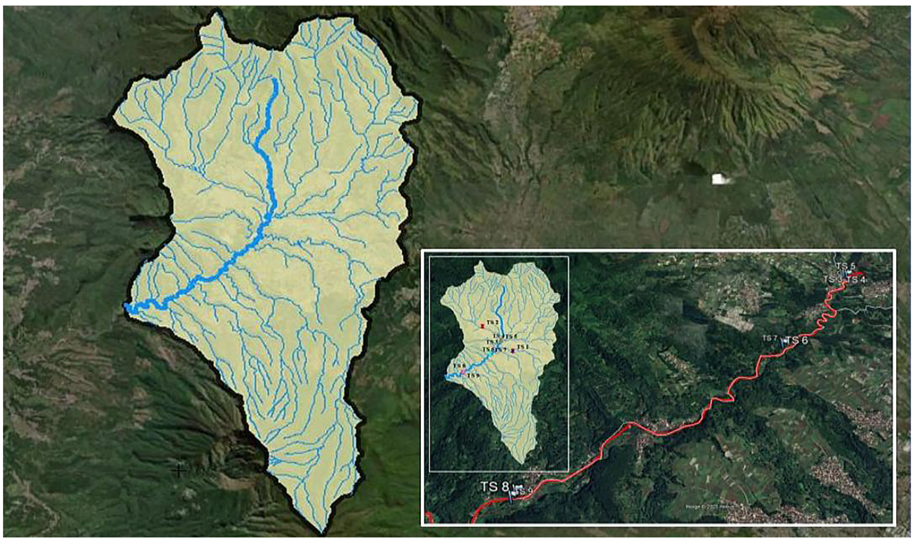


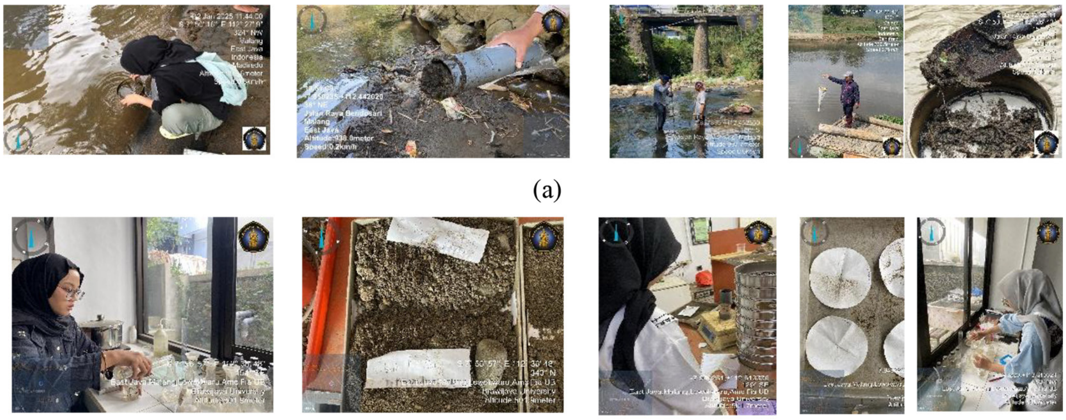
Figure 1. Research location at upstream segment of the upper Konto sub-watershed

Figure 2. Sites for water and sediment sampling

Figure 3. Research equipment and instruments, (a) Horiba U-20, (b) plankton net No. 20, (c) sieve shaker, (d) Hydrion AM-40 ammonia test kit, (e) USDH-48, (f) LAQUAtwin NO_3 nitrate test kit

The sediment nutrient concentration (N, P and K) analysis using the standardized soil and sediment chemistry methods. Grain-size distribution was carried out based on the AASHTO classification separating sediment into gravel, sand and silt-clay fractions. Quadrat transects were employed in sampling macroinvertebrates to show spatial variation across greater abundance and distribution. The inverse distance weighted (IDW) interpolation technique was used to find the spatial patterns of water and sediment quality, based on previous research by (Li and Heap, 2014). Water quality status was evaluated using PI, whereas ecological condition was assessed using the FBI. The PI was calculated as follows:

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



(a)

(b)

Figure 4. Field data collection and laboratory testing activities: (a) field activity for data collecting, (b) laboratory activity

where: *PIj* – pollution index for designated use *j*; *Ci* – measured concentration of water quality parameter *I*; *Lij* – standard concentration limit for parameter *i* under use category *j*; (*Ci/Lij*) *R* – mean value of the ratio (*Ci*/*Lij*); (*Ci*/*Lij*) *M* – maximum value of the ratio (*Ci/Lij*).

PI values were interpreted as follows: 0–1.0 – good quality; 1.1–5.0 – lightly polluted; 5.1–10 – moderately polluted; and >10 – heavily polluted.

Macroinvertebrate data were subsequently used to calculate FBI as follows:

$$FBI = \frac{\sum x_i t_i}{n} \quad (2)$$

where: x_i – number of individuals in family *I*; t_i – tolerance value of family *I*; *n* – total number of individuals across all families.

FBI values were classified as: 0.00–3.75 = excellent; 3.76–4.25 = very good; 4.26–5.00 = good; 5.01–5.75 = fair; 5.76–6.50 = marginal; 6.51–7.25 = poor; and 7.26–10.00 = very poor. Taxa were further grouped into sensitive (0–3), moderately tolerant (4–6), and tolerant (7–10) categories (Hilsenhoff, 1988). Water quality was assessed using the FBI, varying from 0.00–3.75 reflecting excellent quality and the lack of organic pollution, 3.76–4.25 as very good quality with slight organics pollution, 4.26–5.00 as good quality with moderate organic pollution, 5.01–5.75 under fair quality with rather heavy pollution, 5.76–6.50 as marginal quality with heavy pollution, 6.51–7.25 poor quality (very heavy) to attain very poor status (7.26–10) corresponding to severe organic pollution.

RESULTS AND DISCUSSION

The upstream segment of the Upper Konto sub-watershed, sourced from Mount Anjasmoro and Mount Argowayang and flowing past Tawangsari and Maron, is predominantly influenced by agricultural, livestock, and residential activities, resulting in a greenish-brown river coloration indicative of organic waste inputs.

Field investigations encompassed nine sampling points for water quality and sediment, along with four organic waste deposition sites, selected based on accessibility, river conditions, biotic observation space, and land-use features. Water quality data (physical and chemical parameters) is presented in Table 1.

Water quality data in Table 1 show clear differences between dry and rainy seasons across the sampling locations. Overall, pH values remained near neutral to slightly alkaline, ranging from about 6.94 to 7.92, which indicates that the water was generally within a normal range for natural waters. During the rainy season, several parameters such as TSS, turbidity, and TOM tended to increase in some locations, suggesting that rainfall may carry suspended particles, organic matter, and surface runoff into the water bodies. For example, turbidity was very high at TS 1 in both seasons, showing that this location may receive more sediment or disturbance than the others. Meanwhile, DO values were generally higher during the rainy season, which may be linked to increased water movement and aeration from rainfall. TDS and conductivity were mostly lower in the rainy season, indicating dilution by rainwater, although some locations still showed

Table 1. Water quality data (physical and chemical parameters)

Parameter	Season	Location								
		TS 1	TS 2	TS 3	TS 4	TS 5	TS 6	TS 7	TS 8	TS 9
pH	Dry	7.32	7.39	7.87	7.82	7.92	7.75	7.43	7.75	7.82
	Rainy	6.94	7.27	7.28	-	7.37	7.45	7.36	7.52	7.50
TSS (mg/L)	Dry	270.00	170.00	240.00	190.00	350.00	210.00	150.00	130.00	80.00
	Rainy	260.00	280.00	280.00	-	300.00	290.00	210.00	210.00	140.00
TDS (mg/L)	Dry	324.25	125.00	197.75	186.50	199.50	203.50	197.75	213.75	151.25
	Rainy	169.00	54.25	127.33	-	121.75	130.00	183.75	144.75	151.00
Temperature (°C)	Dry	24.76	24.27	24.55	24.51	23.95	22.77	24.00	24.36	23.37
	Rainy	21.07	22.85	24.24	-	24.33	24.33	24.40	23.58	24.41
Turbidity (NTU)	Dry	166.48	28.83	123.25	80.05	138.93	88.15	38.35	70.63	14.54
	Rainy	153.50	65.63	153.67	-	109.25	174.25	64.90	90.33	43.35
DO (mg/L)	Dry	4.95	5.57	7.09	7.06	6.65	7.81	6.85	7.82	7.84
	Rainy	7.49	7.95	7.69	-	6.82	7.34	6.49	7.61	7.32
Conductivity (S/m)	Dry	505.25	192.25	304.50	287.25	307.00	313.00	304.25	328.75	233.00
	Rainy	259.50	84.00	196.33	-	187.50	155.50	282.25	223.00	232.25
TOM (ppm)	Dry	149.00	18.60	39.18	23.74	27.18	32.32	23.74	40.90	11.73
	Rainy	79.00	39.19	70.07	-	35.75	44.33	40.90	65.78	48.63
NO_3 (ppm)	Dry	43.00	14.00	36.00	25.00	37.00	60.00	16.00	29.00	19.00
	Rainy	27.00	9.00	17.00	-	20.00	21.00	36.00	49.00	23.00
NH_3 (ppm)	Dry	5.00	5.00	5.00	5.00	5.00	10.00	10.00	5.00	5.00
	Rainy	5.00	5.00	5.00	-	5.00	10.00	5.00	5.00	5.00
N total (ppm)	Rainy	73.96	40.63	86.46	-	57.29	43.13	50.00	73.13	66.04
P total (ppm)	Rainy	52.01	25.67	41.74	-	33.93	27.90	25.00	46.65	30.80
K total (ppm)	Rainy	190.32	185.11	185.00	-	192.98	183.94	175.85	24.82	24.83

relatively high mineral content. Nutrient levels such as nitrate, ammonia, nitrogen, phosphorus, and potassium varied among locations, suggesting different local influences, possibly from agricultural runoff, domestic waste, or natural soil inputs. In general, the table suggests that rainfall strongly affects water quality by diluting dissolved substances while increasing suspended materials and organic pollution in certain areas.

Seasonal ecohydraulic controls on river condition

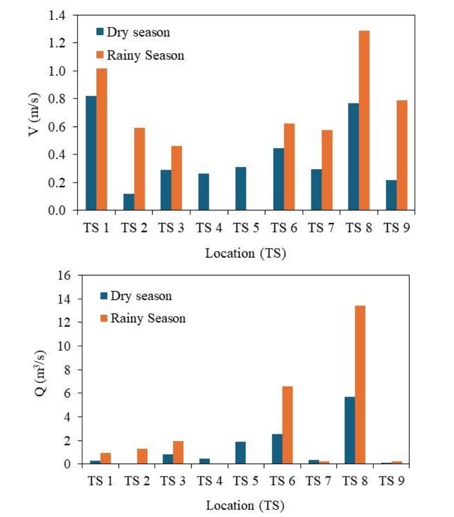
The upstream segment of the Upper Konto sub-watershed is heavily impacted by agriculture, livestock, and settlements, which generate organic waste that flows into the river system. In low-velocity segments, waste deposits remained more exposed during the dry season, as observed in the field; however, during the rainy season, higher discharges increased sediment transport, burying organic deposits beneath sandy substrates. At the same time, sand still dominated as bed material across sites, suggesting that seasonal hydraulic processes have strong control over sediment deposition and thus benthic habitat configuration.

The river hydraulic parameters during the dry and rainy seasons at each location are presented in Table 2. Variations in river discharge illustrate the impact of flow variability on water quality and sediment dynamics in the upstream segment of the Upper Konto sub-watershed.

Data on river discharge measurements were obtained from direct field/skimming observations of water pH upstream in the Upper Konto sub-watershed, and exhibited a clear seasonal pattern. Discharge values varied between 0.038–5.688 m^3/s in the dry season, rising to 0.23–13.404 m^3/s during the rainy season, with TS8 being the station with the most comparable increase in discharge. Similarly, flow velocity ranged from 0.12–0.82 m/s during the dry season to 0.46–1.02 m/s between rainy seasons, indicating the effect of hydraulic processes on river morphology, substrate dynamics, and

Table 2. River hydraulic parameters

Location	Flow velocity (m/s)	Discharge (m^3/s)	Flow velocity (m/s)	Discharge (m^3/s)
	Dry season		Rainy season	
TS 1	0.821	0.271	1.015	0.913
TS 2	0.120	0.038	0.589	1.280
TS 3	0.290	0.836	0.461	1.976
TS 4	0.264	0.473	–	–
TS 5	0.311	1.887	–	–
TS 6	0.444	2.555	0.623	6.600
TS 7	0.293	0.331	0.576	0.230
TS 8	0.769	5.688	1.289	13.404
TS 9	0.217	0.120	0.790	0.253



aquatic biota. This variance following a steep cuspate slope is typical of a curving river system and has direct implications for sediment deposition, riparian cover, and macroinvertebrate diversity, but, as with the ecohydraulic model, it also indicates the role that discharge variability will play through water-quality effects on local ecosystem processes. Specifically, TS8 observed the greatest variation in flow velocity and discharge between seasons, indicating a pronounced ecohydraulic influence of rainfall-induced flow variability on sediment transport dynamics and macroinvertebrate colonization patterns over time.

Hydrological variability is a key driver of substrate disturbance and sediment mobilization in streams; it can be assessed by examining discharge or flow velocity, which both increase significantly during the rainy season. These findings suggest that river condition in the Upper Konto is influenced by both pollutant loading and ecohydraulic processes, linking habitat quality and ecological responses. Similar interactions among flow variability, habitat condition, and benthic assemblages have been documented in other river systems (Woś and Książek, 2022; Vagenas et al., 2024).

Riparian vegetation and ecological buffering

The riparian vegetation of the study reach is composed of bamboo, sengon, taro, watercress,

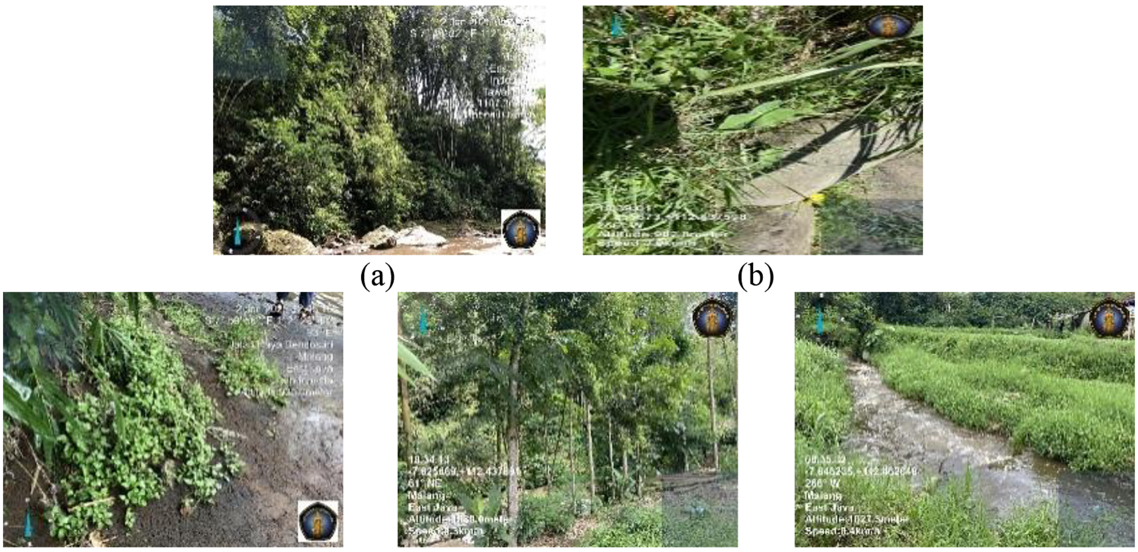

(a) (b) (c) (d) (e)

Figure 5. Riparian vegetation along the river course: (a) bamboo plant, (b) *Colocasia esculenta* (taro), (c) watercress plant, (d) Fabaceae (sengon), (e) kumpai grass

and kumpai grass (Figure 5). They provide bank stabilization, erosion control, and pollutant retention, and several may also contribute to phytoremediation via nutrient uptake and microbially mediated transformations. These taxa point out that riparian corridors act as biological oases, providing hydration that alleviates declines in water quality driven by chronic land-use pressure (Naiman et al., 1993; Sweeney and Newbold, 2014). The interpretation aligns with studies showing that intact riparian vegetation enhances river resilience and improves water quality (Brumberg et al., 2021; Granitto et al., 2025).

Macroinvertebrate response to ecological disturbance

The macroinvertebrate assemblages were dominated by tolerant taxa, including Lumbricidae, Chironomidae, and *Radix rubiginosa*, while sensitive taxa, such as Plecoptera, were absent (Figure 6). Such a community structure is typical for systems that are persistently stressed and receive high organic inputs. Declining taxonomic richness during the rainy season indicates that increased discharge may temporarily dilute dissolved pollutants but, at the same time, exacerbate ecological disruption through substrate instability, turbidity, and habitat disturbance. Declining taxonomic richness during the rainy season indicates that increased discharge may temporarily dilute dissolved pollutants but, at the same time, intensify ecological disruption through substrate instability, turbidity, and habitat disturbance (Hilsenhoff, 1988; Metcalfe, 1989; Chang et al., 2014; Bilalli et al., 2022). This pattern is consistent with biological assessment studies showing that wastewater and other anthropogenic discharges reduce macroinvertebrate diversity and shift assemblages toward pollution-tolerant taxa (Ilham et al., 2022). These results support the use of macroinvertebrates to assess cumulative ecological degradation that might escape detection by instantaneous physicochemical measurements.

The dominance of tolerant families such as Naididae (450 individuals) and Lymnaeidae (113 individuals) further confirms organic pollution and habitat degradation (Table 3). These taxa are known to thrive in low-oxygen and nutrient-rich environments, making them reliable indicators of anthropogenic disturbance. Conversely, sensitive families such as Perlidae, Cordulegastridae, and Calopterygidae were either rare or absent, underscoring a loss of biodiversity and ecological function in most locations (Tables 3–5).

Divergence between PI and FBI

A key finding of this study is the divergence between physicochemical and biological assessments. In both seasons, PI classified most sites as lightly to moderately polluted, while FBI indicated fair to very poor ecological condition, but only during the rainy season. This discrepancy

Figure 6. The most abundant macroinvertebrate, (a) common earthworm, (b) red earthworm, (c) *Radix rubiginosa*, (d) *Corbicula fluminea*, (e) common water strider, (f) ebony jewelwing

Table 3. Macroinvertebrates family

Family	Amount	Family	Amount	Family	Amount
Chrysomelidae	19	Formicidae	7	Tettigoniidae	2
Gerridae	51	Erebidae	1	Potamidae	1
Lumbricidae	43	Syrphidae	2	Entomobtyidae	3
Acrididae	8	Tetragnatha	1	Theridiidae	1
Bibionidae	3	Colletidae	1	Perlidae	1
Nymphalidae	3	Stenopelmatidae	4	Calopterygidae	3
Lymnaeidae	113	Gryllidae	2	Dendrobatidae	1
Bufonidae	24	Cordulegastridae	1	Lestidae	1
Isotomidae	2	Viviparidae	1	Coenagrionidae	2
Pisauridae	1	Libellulidae	2	Prosorhochmidae	7
Poeciliidae	6	Cerambycidae	3	Tetragnathidae	1
Naididae	450	Muscidae	10	Flatidae	4
Pieridae	3	Tridactylidae	7	Tetrigidae	2
Sphaeroceridae	2	Micropezidae	1		

Table 4. Summary of pollution index values during the dry and rainy seasons

Location	PI dry season	Status	PI rainy season	Status
TS 1	5.23	Moderately polluted	4.59	Lightly polluted
TS 2	4.36	Lightly polluted	4.43	Lightly polluted
TS 3	4.52	Lightly polluted	4.51	Lightly polluted
TS 4	4.44	Lightly polluted	-	-
TS 5	4.54	Lightly polluted	4.47	Lightly polluted
TS 6	5.57	Moderately polluted	5.54	Moderately polluted
TS 7	5.45	Moderately polluted	4.48	Lightly polluted
TS 8	4.46	Lightly polluted	4.53	Lightly polluted
TS 9	4.33	Lightly polluted	4.42	Lightly polluted

Table 5. Summary of family biotic index values during the dry and rainy seasons

Location	FBI dry season	Status	FBI rainy season	Status
TS 1	6.43	Marginal	6.98	Poor
TS 2	6.47	Marginal	8.00	Very poor
TS 3	6.55	Poor	8	Very poor
TS 4	5.10	Fair	-	-
TS 5	7.39	Very poor	5.00	Fair
TS 6	6.69	Poor	8.00	Very poor
TS 7	6.14	Marginal	7.00	Poor
TS 8	7.27	Very poor	6.74	Poor
TS 9	5.77	Marginal	6.80	Poor

indicates that physicochemical indicators primarily reflect short-term conditions in the water column, whereas biological indicators integrate longer-term ecological responses to habitat change, hydrological perturbation, and chronic organic loading. Comparable bioassessment results from river systems affected by agricultural, urban, and industrial pressures show that macroinvertebrate-based indices are sensitive to spatial differences in pollution sources and can

Table 6. Sediment characteristics data

Location	Composition (%)		
	Gravel	Sand	Mud
TS 1	40.79	57.57	1.64
TS 2 Right side	13.57	61.71	4.72
TS 2 Left side	2.34	89.45	8.20
TS 3	35.33	63.93	0.75
TS 4 Left side	39.89	58.98	1.13
TS 4 Middle	2.87	90.91	6.22
TS 5 Left side	6.02	83.13	10.84
TS 5 Middle	2.42	94.93	2.66
TS 6 Right side	60.79	38.99	0.22
TS 6 Left side	45.22	53.80	0.98
TS 7	19.88	78.36	1.75
TS 8 Right side	48.40	51.10	0.51
TS 8 Middle	76.64	23.04	0.32
TS 9	22.12	75.81	2.07
TS Organic waste deposits 1	3.23	93.01	3.76
TS Organic waste deposits 2	7.50	89.17	3.33
TS Organic waste deposits 3	3.67	91.74	4.59
TS Organic waste deposits 4	3.09	91.77	5.14

reveal water-quality degradation through reduced richness and diversity (Ilham et al., 2022). This divergence is ecologically significant because it shows that using physicochemical parameters in isolation can fail to reflect the extent of ecological degradation in hydrologically dynamic tropical rivers. By extending PI and FBI, our integrated approach enables a more comprehensive assessment of river condition and demonstrates the enhanced analytical value of biological metrics during seasons when flow conditions change. Other ecohydraulic investigations have reported similar findings, highlighting the greater responsiveness of biological indicators (BIs) to ecological impairment than physicochemical parameters alone (Sedighkia and Datta, 2023).

The FBI values for sampling points TS1–TS9 indicated seasonal variations in organic pollution levels, with dry-season FBI scores ranging from 5.10 to 7.39 and rainy-season scores ranging from 5.00 to 8.00. In the dry season, marginal to poor conditions were recorded at most sites, with TS5 and TS8 showing very poor conditions (Fibure 7a). During the rainy season, the values of the FBI increased at some sites (especially TS2, which was renewed at a very poor level), indicating that these waters are severely polluted with organic matter. Mark improvement from very poor to fair was demonstrated by TS5, while for the rainy season, there is a lack of data in TS4 (Figure 7b). Higher FBI values and deteriorating water quality at most sampling points during the rainy season suggest greater organic pollution during periods of higher discharge.

a) b)

Figure 7. Pollution index mapping during dry season and rainy season: (a) pollution index mapping during the dry season, (b) pollution index mapping during the rainy season

Figure 8. Sites for organic waste deposits

Sediment nutrient enrichment and ecological consequences

However, despite the prevalence of sandy sediments, bed sediments held significant concentrations of nitrogen, phosphorus, and potassium, suggesting that the riverbed serves not only as physical habitat but also as a nutrient sink. Additionally, this nutrient enrichment likely contributed to ongoing ecological stress in depositional zones by supporting oxygen-depleting (i.e., tolerant) taxa, thereby further reducing oxygen availability. Accordingly, within the context of nutrients, sediments are components of the ecohydraulic system that must be considered active factors with direct relevance to nutrient cycling, habitat quality, and benthic community responses (Carpenter et al., 1998; Ji et al., 2024).

Studies conducted in the Upper Konto subwatershed indicated seasonal variations in river condition and sediment. In the dry season, flows were greenish-brown due to organic effluents from agriculture and livestock, particularly near settlements. During the rainy season, higher discharge led to darker water and buried waste beneath sandy sediments. The right tributary (Manting river) was calmer, and waste was deposited along its banks, reducing transport capacity during the dry season, while the left tributaries (Ngroto river and Mantung river) experienced rapid increases in discharge and rapid color changes during the rainy season. In the dry season, waste was collected for the Konto river to cover it with sand in the rainy season. The Grojogan Sewu river remains transparent in the dry season but slightly turbid during heavy rainfall. The analysis of sediments indicated that across sites TS1–TS14, sand was the dominant substrate, followed by gravel and mud in lesser amounts, with livestock waste being a major contributor (Figure 8). In general, agricultural and residential activities impacted river conditions and sediment composition. Table 6 provides a recapitulation of sediment characteristics obtained from the upstream segment of the Upper Konto sub-watershed.

Microscopic examination of the filter paper was conducted to identify retained particles and assess sediment characteristics. Organic matter originating naturally within aquatic ecosystems is produced through processes including decomposition, degradation, and the breakdown of organic waste and biological remnants. These processes yield suspended organic particles in the water body, whose accumulation elevates suspended solid concentrations and, in turn, influences water quality and the ecological equilibrium of the aquatic environment.

Novelty and broader implication

The main novelty of this work is that it integrates physicochemical evaluation (PI), biological response (FBI), sediment nutrient dynamics, and riparian vegetation functions within a common ecohydraulic framework applied to a tropical highland river. This approach broadens traditional river-quality assessment beyond water chemistry and illustrates how seasonal hydrological variability can obscure ecological degradation when assessment relies solely on physicochemical metrics.

The study's findings emphasize that, for effective watershed monitoring, physicochemical, biological, and sediment organisms should be monitored simultaneously from a leadership perspective. Thus, improving riparian protection and reducing the volume of untreated livestock n-fuel waste inputs must be undertaken to enhance ecological conditions in the Upper Konto sub-watershed and protect Selorejo reservoir water quality downstream. These findings also reinforce the need to place macroinvertebrate-based assessment within a broader ecohydraulic framework. While previous studies have demonstrated the value of macroinvertebrate diversity and biotic indices for detecting pollution gradients (Ilham et al., 2022; Bilalli et al., 2022), the present study extends this perspective by linking biological response with seasonal discharge variation, sediment nutrient enrichment, and riparian vegetation function in a tropical highland headwater system.

CONCLUSIONS

This study confirms that physicochemical assessment alone is insufficient to characterize ecological condition in hydrologically dynamic tropical headwater systems. The hypothesis that biological indicators provide a more integrative and sensitive measure of ecological degradation under seasonal flow variability is supported by the observed divergence between PI and FBI classifications. The results demonstrate that, although water quality indices (PI) indicated light to moderate pollution levels, biological responses (FBI) revealed substantially degraded ecological conditions, particularly during the rainy season. This confirms that macroinvertebrate assemblages integrate cumulative impacts of hydrological disturbance, sediment dynamics, and chronic organic loading that are not captured by instantaneous physicochemical measurements.

A key novel finding of this study is the explicit linkage between seasonal ecohydraulic variability, sediment nutrient enrichment, riparian vegetation structure, and biological degradation within a single analytical framework. This integrated perspective reveals that hydrological fluctuations play a decisive role in reshaping habitat conditions and biotic communities, thereby masking ecological impairment when assessment relies solely on water chemistry.

The main knowledge gap addressed by this study is the lack of multi-compartment river health assessments that simultaneously integrate water quality, sediment processes, biological responses, and riparian functions in tropical highland headwaters. By filling this gap, the study provides a more holistic diagnostic framework for river ecosystem assessment.

These findings open perspectives for developing more robust watershed monitoring strategies that combine biological indices with hydrological and sediment-based indicators, particularly in agricultural catchments where seasonal discharge variability strongly influences ecological interpretation.

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