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Assessment of Water Quality and Pollution Load Capacity in a Taluduyunu River, Gorontalo Province: The Impact of Artisanal Gold Mining Activities

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ABSTRACT

Artisanal small-scale gold mining (ASGM), locally known as PETI (*Penambangan Emas Tanpa Izin*), has substantially altered the upstream Taluduyunu River in Pohuwato Regency, Gorontalo Province, a reach supplying drinking water to roughly 19,686 residents through PDAM Tirta Maleo. To quantify the scale of this degradation, water quality was assessed at four stations across the disturbance gradient during the 2023 dry season, covering 24 physicochemical parameters against Class II standards (PP 22/2021). Among all parameters measured, only total suspended solids (TSS) exceeded regulatory thresholds. At SR3, the most intensively mined station, TSS reached 21,000 mg/L, 420 times the 50 mg/L Class II limit, while BOD and COD remained below detection limits at all locations. The pollution index (PI) placed SR3 in the heavily polluted category (PI = 10.01) and SR2 and SR4 in the moderately polluted range. Actual TSS loads exceeded assimilative capacity (TMDL) by approximately 100-fold: BPA = 5,237,913.6 kg/day against BPM = 52,272 kg/day, leaving a deficit of roughly 5.2 million kg/day and requiring a 99 % load reduction for compliance. Multi-stakeholder analytic hierarchy process (AHP) analysis ranked TMDL determination (weight 0.341) and river classification (0.264) as the most urgent interventions, ahead of community outreach, monitoring, and law enforcement. The combined TMDL–AHP approach developed here may transfer to other ASGM-impacted watersheds, contributing to SDG 6 and SDG 15 objectives.

Introduction

Small-scale gold mining has become one of the most challenging factors contributing to freshwater degradation in Indonesia's tropical regions. In river basins where miners dig active channels a method that erodes riparian vegetation, loosens alluvial material, and discharges waste directly into the river. The river visually appears murky and brown; even at the SR3 site, the water flows rapidly, carrying a mixture of sediment and rock. The riverbanks are covered with sediment and rock from upstream mining activities. Suspended sediment concentrations can reach levels unsuitable even for the most tolerant aquatic communities. Recent field studies confirm that artisanal small-scale gold mining (ASGM) systematically generates elevated suspended sediment, heavy metal contamination, and hazardous chemical inputs across Southeast Asian, African, and Latin American river systems [1,2]. Mining-related sediment and metal loading threaten aquatic biota and have been linked to local fish population collapses [3]. At the global scale, gold mining has measurably increased sediment fluxes in tropical waterways across multiple regions [4]. In Ghana's Oda River, Total suspended solids (TSS) at mining-affected sites ran between 438 and 1,755 mg/L, far above any drinking water threshold [1]. Along Cameroon's Lom River, TSS reached 47.6–471 mg/L with turbidity of 117–510 NTU, directly tied to gold extraction activity [2].

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In Colombia's Suárez watershed, traditional mining kept TSS at 100–500 mg/L alongside persistently elevated turbidity [5]. High sediment loads suppress light penetration, bury benthic habitat, and carry mercury and other contaminants downstream [6,7]. Taluduyunu River in Pohuwato Regency captures these pressures at a local scale. This 8.3 km reach within the Marisa Watershed functions as the raw water intake for PDAM Tirta Maleo, whose service area covers approximately 19,686 residents. Since the early 2010s, excavator-based PETI (*Penambangan Emas Tanpa Izin*) operations have progressively altered the river's physical character: channel banks are destabilized, riparian cover has been cleared over much of the active mining zone, and the water runs visibly brown or dark brown through most of the reach. During the July 2023 survey, the water along zones SR2–SR3 was a deep, dark brown even in the morning when flow was at its lowest, and the smell of soil could be detected from a distance of approximately 10 meters from the riverbank. The research in analogous Indonesian settings consistently shows ASGM sites producing water quality parameters that exceed national standards, with suspended sediment and heavy metal accumulation in sediments as the most prominent concerns [7,8].

Addressing pollution in a river that simultaneously serves as a drinking water source and an active mining zone demands a quantitative regulatory foundation [8]. The Indonesian concept of total maximum daily load (TMDL) in the river can receive without breaching designated-use standards, provides exactly that foundation, yet prior TMDL assessments in Indonesia have generally been single-site, technically focused, and disconnected from governance prioritization [9]. This study was designed to fill that gap. Two questions guided the work: Does PETI activity push sediment loads past the Taluduyunu River's assimilative capacity, and by how much? And among the management options available, which do key local stakeholders judge most urgent? To answer them, we assessed water quality at four stations spanning the full disturbance gradient, quantified actual pollution loads using mass-balance methods, determined TMDL, and applied the analytic hierarchy process (AHP) to structure stakeholder input into ranked priorities [10]. Integrating TMDL assessment with participatory multi-criteria decision analysis of this kind has not previously been reported for an Indonesian ASGM watershed, and the combined approach may offer a transferable governance model for comparable settings elsewhere, in support of SDG 6 and SDG 15 [11].

Materials and Methods

Study Sites

Field work was carried out in the upper Taluduyunu River, Hulawa Village, Buntulia Subdistrict, Pohuwato Regency, Gorontalo Province. The study encompasses an 8.3 km river segment draining a catchment of approximately 268.31 km² within the Marisa Watershed (Figure 1). Water and discharge data were gathered from July to August 2023, the dry season, which, according to Decision of the Minister of Environment Number 110/2003 (Kepmen LH 110/2003) Concerning Guidelines for Determining the Pollution Load Capacity of Water Resources (Article 2, paragraph 2), represents minimum flow conditions as a conservative scenario appropriate for TMDL determination. Restricting sampling to the dry season acknowledges seasonal representativeness as a study limitation; multi-season monitoring is recommended as a next step. During the data collection period, there was no rainfall for at least 2 consecutive days before sampling, ensuring baseflow conditions were unaffected by surface runoff. Data processing and analysis ran from September 2023 through December 2024.

Station placement followed a spatial overlay of PETI activity distribution and river network configuration to ensure coverage of the complete pollution gradient. Four stations were established (Table 1): SR1 at the undisturbed headwater upstream of any mining influence, SR2 and SR3 within progressively more intensively worked mining zones, and SR4 downstream of the main mining complex, just before confluence with the Botudolanga River. SR1 has denser riparian vegetation compared to other sampling sites. The substrate is dominated by gravel and rocks; SR2-SR4 show active erosion with a scour width reaching ± 10 m from the original riverbank (Figure 1). Coordinates were recorded with a Garmin Montana GPS unit (± 3 m horizontal accuracy). All spatial data use UTM Zone 51N, WGS 84 datum; the base map derives from BIG (*Badan Informasi Geospasial*) 1:25,000 national topographic grids; cartographic outputs were produced in QGIS 3.28 and exported at 600 dpi.

Table 1. Geographic coordinates and physical characteristics of four water quality sampling locations in the upstream Taluduyunu River, Pohuwato Regency, Gorontalo Province, Indonesia. The sampling design spans a complete spatial gradient from SR1, a pristine headwater reference station with intact riparian vegetation (70–80% canopy cover), through SR2 and SR3 as active artisanal gold mining (PETI) zones of increasing intensity, to SR4 as the most downstream station before confluence with the Botudolanga River. GPS coordinates were recorded using a Garmin Montana device (± 3 m horizontal accuracy); all spatial data are projected in UTM Zone 51N, WGS 84 datum.

No	Location code	Location name	Coordinates	Description
1	SR1	Headwater (*Air Terang*)	N: 0°34'24.232" E: 121°58'19.424"	Pristine headwaters upstream of mining activities are characterized by intact riparian vegetation (70–80% canopy cover), clear water, and substrates dominated by cobbles and gravel. This location served as the baseline reference for the natural water quality conditions.
2	SR2	Mining Area 1	N: 0°34'20.959" E: 121°58'22.591"	Active mining zone with excavator units operating simultaneously for material extraction. Riparian vegetation was significantly degraded on exposed banks. The water exhibited high turbidity with a brownish coloration due to elevated suspended sediment loading.
3	SR3	Mining Area 2	N: 0°34'5.443" E: 121°58'27.668"	The highest-intensity mining zone has excavator units and active gold processing using amalgamation methods. Severe riparian degradation with extensive bank erosion is observed. The water is extremely turbid and dark brown, indicating maximum sediment pollution.
4	SR4	Mining Area 3	N: 0°33'11.515" E: 121°58'12.060"	Downstream mining location before confluence with the Botudolanga River, representing cumulative impacts from upstream activities. Moderate mining intensity with 2–3 excavator units. Water quality reflects the combined effects of all upstream pollutants.

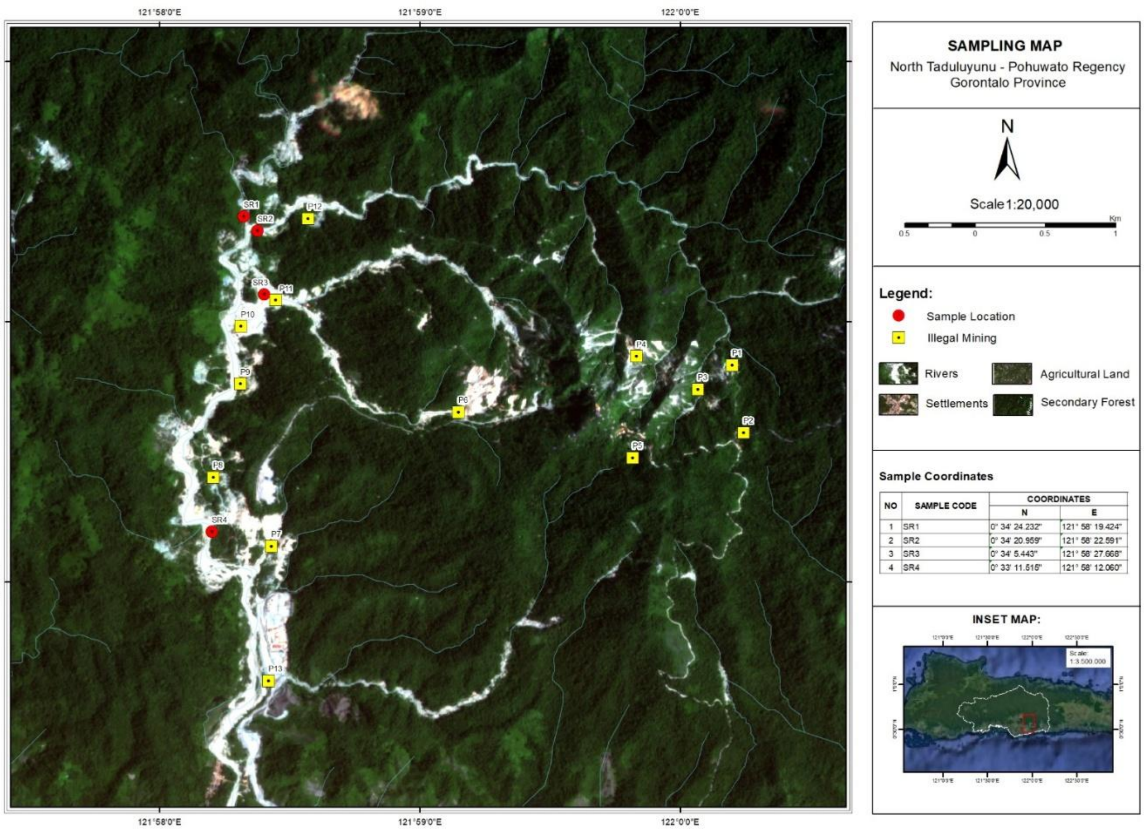

Figure 1. Sampling map showing the spatial distribution of four monitoring stations (SR1–SR4) along the upstream Taluduyunu River, Pohuwato Regency, Gorontalo Province, Indonesia, overlaid on a satellite base map. Red polygons denote active illegal gold mining (PETI) zones; yellow lines represent river channels within the study reach. SR1 is located at the pristine headwater, while SR2–SR4 correspond to progressively impacted mining zones downstream. The base map was sourced from the Indonesian Geospatial Information Agency (BIG) at a scale of 1:25,000; cartographic outputs were generated using QGIS 3.28 and exported at 600 dpi (UTM Zone 51N, WGS 84).

Data Collection Methods

Water Quality Sampling and Analysis

At each station, three grab samples were drawn from the central surface layer (0.3 m depth) during stable flow, collected in pre-cleaned polyethylene bottles following standard environmental protocols. TSS samples went into 1-litre bottles; chemical analyses used 500-mL containers. pH, temperature, TDS, and turbidity were recorded in situ with a calibrated Hanna Instruments HI98194 multiparameter meter immediately after sample collection to capture parameters that shift quickly after removal from the water body. Sampling was conducted between 8:00 a.m and 11:00 a.m WITA (*Waktu Indonesia Tengah*) under stable flow conditions, with no mechanical disturbance from excavators within a radius of approximately 50 meters from the sampling point to minimize local turbulence. All samples were analyzed at RND Teknologi Indonesia, an environmental testing laboratory accredited by KAN (*Komite Akreditasi Nasional*) under ISO 17025 for wastewater and surface water parameters. Analysis followed Indonesian National Standards (*Standar Nasional Indonesia*) and standard methods for the water and waste water testing [12]. The full 24-parameter suite covered physical indicators (TSS, TDS, temperature, turbidity), chemical indicators (pH, BOD, COD, DO, nutrients, cyanide, oil and grease), and heavy metals (mercury, arsenic, cadmium, lead, zinc, selenium, cobalt). Gravimetric analysis was used for TSS, titrimetry for biochemical oxygen demand (BOD), spectrophotometry for chemical oxygen demand (COD) and nutrients, and atomic absorption spectrophotometry (AAS) for metals. Method blanks, duplicate samples, and certified reference materials were run throughout to verify analytical reliability.

Hydrological Measurements

Discharge was measured by the velocity-area method using a Global Water FP111 current meter at cross-sections oriented perpendicular to flow. Depth was sounded at 0.5–1.0 m intervals across the full wetted width; velocity was taken at 0.6 D for shallow sections (< 0.75 m) and at 0.2 D and 0.8 D for deeper sections, in line with standard USGS procedure**.** The measured wet width varies from ± 4.2 m at SR1 to ± 10 m at SR3, reflecting channel widening due to excavation; the average depth at SR3 is shallower (± 0.40 m) than at SR1 (± 0.60 m) due to sediment deposition.

Data Analysis Methods

Water Quality Status Assessment

Water quality status was assessed using the Pollution Index (PI) method, which compresses a multi-parameter dataset into a single dimensionless score. For each station, the ratio of measured concentration (Ci) to the relevant Class II standard (Lij) was computed for every parameter; the maximum and mean of these ratios were then combined using Equation 1:

$$PIj = \sqrt{\frac{(Ci/Lij)2M + (Ci/Lij)2R}{2}} \quad (1)$$

where PI_j represents the Pollution Index for designated use j, (*Ci/Lij*)M denotes the maximum ratio among all parameters, and (*Ci/Lij*)R represents the average ratio across all parameters. Water quality was classified into four categories based on PI values: good quality (0.0 ≤ PI ≤ 1.0), slightly polluted (1.0 < PI ≤ 5.0), moderately polluted (5.0 < PI ≤ 10.0), and heavily polluted (PI > 10.0). This classification system provides a standardized framework for communicating water quality status to stakeholders and policymakers.

Pollution Load Calculation

Actual pollution loads for TSS, BOD, and COD were computed at each station by multiplying the measured concentration by the concurrent river discharge, converted to daily mass units using Equation 2:

$$PL = C \times Q \times 86.4 \quad (2)$$

where PL = pollution load (kg/day); C = pollutant concentration (mg/L); Q = river discharge (m^3/s); 86.4 = unit conversion factor. Total load for the study reach was obtained as the cumulative sum across all stations. The spatial pattern of these loads indicates which sub-reaches impose the greatest demand on assimilative capacity and therefore warrant priority management attention.

Pollution Load Carrying Capacity Determination

The pollution load carrying capacity, referred to here by its Indonesian regulatory designation TMDL (Total maximum daily load) in the river reach can receive without the resulting concentration breaching the designated-use standard, as codified in Government Regulation (PP 22/2021) [13]. It was estimated by the mass-balance approach of Kepmen LH 110/2003 (Equation 3):

$$TMDL = (C^{AM} - C^{ba}) \times Q \times 86.4 \quad (3)$$

where CBM = concentration limit from water quality standards (mg/L); Cbackground = natural background concentration at SR1 (mg/L); Q = river discharge (m^3/s); 86.4 = unit conversion factor. Class II thresholds from PP 22/2021 Annex VI were used: TSS = 50 mg/L, BOD = 3 mg/L, COD = 25 mg/L, appropriate for water bodies serving as drinking water sources and for recreational use [14,15]. Where actual load exceeds TMDL, the difference represents the load reduction needed to restore compliance.

Management Strategy Prioritization Using Analytical Hierarchy Process

Management priorities were established using the AHP, a structured multi-criteria decision framework that allows expert judgments from multiple stakeholders to be combined into quantitative priority weights [16]. Four key actor groups were purposively included: a district environmental agency officer, a PETI miners' association representative, a formal mining company environmental officer, and the Hulawa Village head. This composition was chosen to capture both regulatory and operational perspectives on management feasibility.

Pairwise comparisons were administered individually using Saaty's and Vaidya [16,17]. The hierarchy ran from a goal level (river quality restoration) through criteria (government policy, human resources, budget, infrastructure) and actor levels to five management alternatives. Priority weights were calculated by eigenvalue analysis; consistency ratio (CR) < 0.10 was the acceptance threshold. Global weights at the alternatives level were obtained by multiplicative synthesis across all hierarchy levels, normalised to 1.0. The four-respondent panel is acknowledged as a constraint on generalisability; selection was purposive to ensure all key actor groups were represented. Uncertainty in pollution load estimates arising from velocity-area measurements (± 5 to 10%) and the steady-state, instantaneous-mixing assumptions of the TMDL model are noted as technical limitations [18,19]. A summary of the analytical methods used in this study, along with the expected results for assessing water quality status, measuring pollution loads, determining river carrying capacity, and prioritizing management strategies for the upper Taluduyunu River, is presented in Table 2. All statistical analyses were performed using Microsoft Excel 2024.

Table 2. Analytical methods and their expected outputs to assess water quality status, quantify pollution loads, determine river carrying capacity, and prioritize management strategies for the upstream Taluduyunu River, Gorontalo Province, Indonesia (2023). The table summarizes the four main analytical approaches applied in this study. Mathematical equations referenced in the table are presented and numbered sequentially in the main text (Eq. 1–3).

Analysis method	Objective	Expected output
Spatial analysis (overlay and ground check)	Determine optimal locations for water quality sampling based on mining activity distribution and river network configuration.	Strategic sampling location map identifying baseline reference site and progressively impacted zones.
Pollution index (PI) (Equation 1)	Laboratory analysis of water samples to assess compliance with regulatory standards and classify pollution severity.	Water quality status classification (good, slightly polluted, moderately polluted, heavily polluted) for each sampling location.
Pollution load (PL) (Equation 2)	Calculate mass flux of pollutants transported by river flow, where Q is discharge (m^3/s), C is concentration (mg/L), and f is conversion factor (86.4).	Quantified pollution loads (kg/day) for TSS, BOD, and COD at each sampling location, identifying the spatial distribution of pollution sources.
Pollution load carrying capacity (TMDL) (Equation 3)	Determine the maximum pollutant mass the river can assimilate without exceeding water quality standards, comparing actual loads to assimilative capacity.	River carrying capacity values (kg/day) and load reduction targets needed to achieve regulatory compliance.
Analytical hierarchy process (AHP)	Prioritize river management strategies through structured multi-criteria evaluation incorporating stakeholder expert judgments.	Ranked management strategy alternatives with quantified priority weights reflecting stakeholder consensus on implementation sequence.

Results and Discussion

Results

Water Quality Parameters

Water samples from all four stations were analyzed for the full 24-parameter suite against Class II standards under PP 22/2021 Annex VI [13]. Complete results appear in Table 3. Of the 24 parameters, only TSS showed meaningful exceedances; most others fell below detection limits or within regulatory thresholds, consistent with the absence of organic or dissolved chemical pollution sources in an excavator-based PETI operation.

Table 3. Complete water quality parameters measured at four sampling locations in the upstream Taluduyunu River, Pohuwato Regency, Gorontalo Province, Indonesia, during the dry season (July–August 2023), compared against Class II water quality standards (PP 22/2021, Annex VI). A total of 24 physicochemical and heavy metal parameters were analyzed at an ISO 17025-accredited laboratory (RND Teknologi Indonesia). Bold values indicate parameters exceeding the regulatory limit; TSS substantially exceeded the standard at all mining-affected stations, and zinc at SR3 (0.252 mg/L) also exceeded its limit (0.05 mg/L). All other parameters remained within Class II thresholds.

No	Parameter	Unit	Regulation limit	SR1	SR2	SR3	SR4
1	pH	mg/L	(6–9)	7.94	7.96	6.37	7.55
2	TDS	mg/L	1,000	117	69	18	70
3	TSS	mg/L	50	13	2,590	21,000	2,500
4	Fluoride	mg/L	1.5	0.06	0.06	0.04	0.06
5	Sulphide	mg/L	0.002	0.002	0.002	0.002	0.002
6	Free Chlorine	mg/L	0.03	< 0.02	< 0.02	< 0.02	< 0.02
7	Nitrate (NO_3)	mg/L	10	0.091	0.076	0.049	0.094
8	Nitrite (NO_2)	mg/L	0.06	< 0.001	< 0.001	< 0.001	< 0.001
9	Phosphate (Total)	mg/L	0.2	0.034	0.042	0.086	0.023
10	Cyanide (Total)	mg/L	0.02	< 0.005	< 0.005	< 0.005	< 0.005
11	Arsenic	mg/L	1	< 0.005	< 0.005	< 0.005	< 0.005
12	Cadmium	mg/L	0.01	< 0.0001	< 0.0001	0.0026	0.0003
13	Cobalt (Co)	mg/L	0.2	0.05	0.01	0.01	0.01
14	Lead	mg/L	0.03	0.002	0.004	0.03	0.005
15	Selenium	mg/L	0.05	0.005	0.005	0.005	0.005
16	Zinc	mg/L	0.05	< 0.005	< 0.005	0.252	0.009
17	Mercury	mg/L	0.002	< 0.00005	< 0.00005	0.00007	< 0.00005
18	BOD	mg/L	3	< 2	< 2	< 2	< 2
19	COD	mg/L	25	< 10	< 10	< 10	< 10
20	DO	mg/L	4	7.99	7.98	7.98	7.52
21	Oil and grease	mg/L	1	< 1	< 1	< 1	< 1
22	Phenol (Total)	mg/L	0.005	< 0.001	< 0.001	< 0.001	< 0.001
23	Surfactan	mg/L	0.05	0.01	0.01	0.01	0.01
24	BHC	mg/L	210	< 0.00001	< 0.00001	< 0.00001	< 0.00001

TSS rose sharply from 13 mg/L at SR1 — well within the 50 mg/L Class II limit — to 2,590 mg/L at SR2 (51.8× limit), 21,000 mg/L at SR3 (420× limit), and 2,500 mg/L at SR4 (50× limit). BOD and COD were below method detection at all locations (< 2 mg/L and < 10 mg/L), well under the 3 and 25 mg/L thresholds. Oils and fats (< 1 mg/L), total phenols (< 0.001 mg/L), and sulphides (< 0.002 mg/L) were similarly undetected. The overall picture is one of physical sediment loading with virtually no organic or dissolved chemical input, which is characteristic of purely mechanical excavator-based operations. Visually, the SR3 water sample is indistinguishable from liquid mud; the 1-liter sample bottle appears completely opaque (non-translucent) even at a depth of < 1 cm; the physical condition appears consistent with the measured TSS value of 21,000 mg/L.

PI scores and corresponding classification are shown in Table 4. SR1 scored 0.73 (good quality), confirming its suitability as an undisturbed reference. SR2 and SR4 scored 6.78 and 6.73, placing both in the moderately polluted range. SR3 reached 10.01 — the threshold for the heavily polluted category — and the term “heavily polluted” applies in full. Across all three mining-affected stations, TSS was the parameter generating the dominant contribution to the PI score. The PI integrates all measured parameters against Class II standards, with higher values indicating greater pollution severity. Classification thresholds are: good (0.0 ≤ PI ≤ 1.0), slightly polluted (1.0 < PI ≤ 5.0), moderately polluted (5.0 < PI ≤ 10.0), and heavily polluted (PI > 10.0). TSS was the dominant parameter driving PI scores at all mining-affected stations (SR2–SR4), with SR3 classified as heavily polluted (PI = 10.01).

Table 4. Pollution Index (PI) values and corresponding water quality status classification for four sampling locations in the upstream Taluduyunu River, calculated using the method of Decision of the Minister of Environment Number 110/2003.

Location code	Location name	Pollution index (PI)	Water quality status	Dominant parameter
SR1	Headwater (*air terang*)	0.73	Good	TSS
SR2	Mining area 1	6.78	Moderately polluted	TSS
SR3	Mining area 2	10.01	Heavily polluted	TSS
SR4	Mining area 3	6.73	Moderately polluted	TSS
Average	-	6.06	Moderately polluted	TSS

Pollution Load Calculation

Discharge ranged from 1.9 m³/s at SR3 to 6.0 m³/s at SR4. The elevated SR4 discharge reflects its position as the most downstream station, integrating runoff from the full upstream catchment. Calculated loads are in Table 5. Discharge ranged from 1.9 m³/s (SR3) to 6.0 m³/s (SR4). BOD and COD loads were calculated using concentrations below the detection limit as upper-bound estimates; actual organic loads are lower. SR3 recorded the highest TSS load (3,447,360 kg/day), corresponding to the most intensively mined zone, while SR4's elevated discharge reflects its cumulative downstream position, integrating all upstream sub-catchment flows.

Table 5. Pollution loads of TSS, BOD, and COD at four sampling locations in the upstream Taluduyunu River, computed using Equation 2 ($PL = C \times Q \times 86.4$) based on dry-season measurements (July–August 2023).

Location	Discharge (m³/s)	TSS load (kg/day)	BOD load (kg/day)	COD load (kg/day)
SR1	2.0	2,246.40	345.60	1,728
SR2	2.2	492,307.20	380.16	1,900.80
SR3	1.9	3,447,360.00	328.32	1,641.60
SR4	6	1,296,000.00	1,036.80	5,184.00

TSS loads varied by more than three orders of magnitude along the reach. SR1 contributed 2,246 kg/day under natural background conditions. At SR2, the load jumped to 492,307 kg/day; at SR3, the most intensively mined station, it reached 3,447,360 kg/day; and at SR4, partial settling downstream brought it to 1,296,000 kg/day. BOD and COD loads — computed using detection-limit values as upper-bound estimates — varied with discharge rather than with concentration, ranging from 328 to 1,037 kg/day (BOD) and 1,642 to 5,184 kg/day (COD). These represent worst-case values; actual organic loads are lower because all measured concentrations were below the method detection limit.

The spatial pattern along the reach tracks mining intensity closely (Figure 2). SR1 at 13 mg/L sat within the Class II standard, consistent with undisturbed headwater conditions. SR2 recorded 2,590 mg/L (51.8× limit), reflecting the first input of excavator-mobilised material. SR3 peaked at 21,000 mg/L — 420-fold above the regulatory threshold — at the zone where field surveys recorded five to seven excavators working the active channel simultaneously alongside amalgamation processing. Two excavators were observed operating within a 150-meter radius; tailings from the amalgamation process were discharged directly into the river without passing through a settling pond, and the water at that point was a dark, dense brown color SR4 fell to 2,500 mg/L (50× limit), suggesting some gravitational settling in the lower-gradient reach below the main mining zone, though concentrations remained far outside compliance.

The load comparison against TMDL reveals a stark asymmetry across parameters (Figure 3). Total actual TSS load across the reach (BPA = 5,237,913.6 kg/day, approximately 5,238 ton/day) exceeded the maximum allowable load (BPM = 52,272 kg/day, approximately 52.3 ton/day) by roughly 100-fold, resulting in a carrying-capacity deficit (TMDL) of −5,185,641.6 kg/day. Closing that gap would require approximately a 99 % reduction in TSS loading. BOD used 67% of its carrying capacity and COD just 40%, both well within assimilative limits. This contrast confirms that the problem is physical sediment disturbance, not organic or dissolved chemical discharge, a signature consistent with excavator-based ASGM [1,7,20].

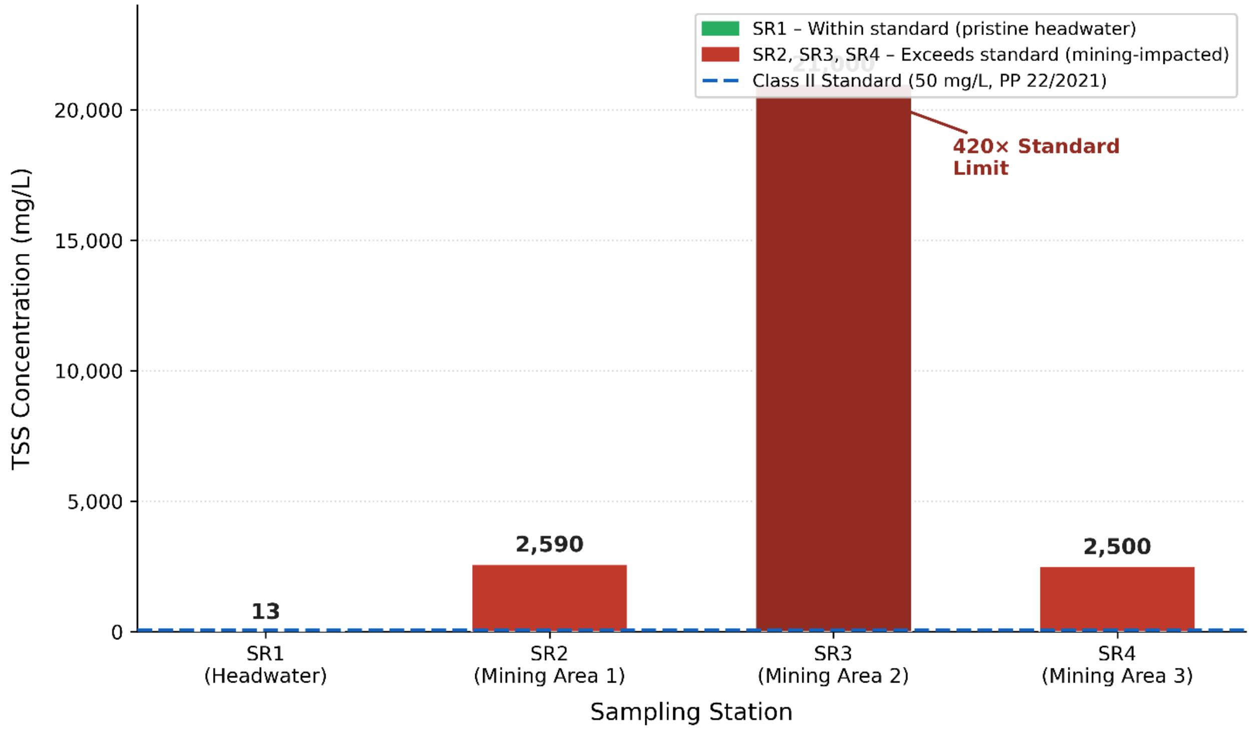

Figure 2. Spatial distribution of TSS concentration across four sampling stations (SR1–SR4) along the upstream Taluduyunu River, measured during the dry season (July–August 2023). The dashed horizontal line indicates the Class II water quality standard of 50 mg/L (PP 22/2021, Annex VI). Values above each bar denote measured TSS concentrations (mg/L). SR1 (13 mg/L) remained within the standard, while SR2, SR3, and SR4 exceeded the limit by factors of 51.8 times, 420 times, and 50 times, respectively. SR3 recorded the highest value of 21,000 mg/L, representing one of the most severe exceedances documented in the Indonesian ASGM literature.

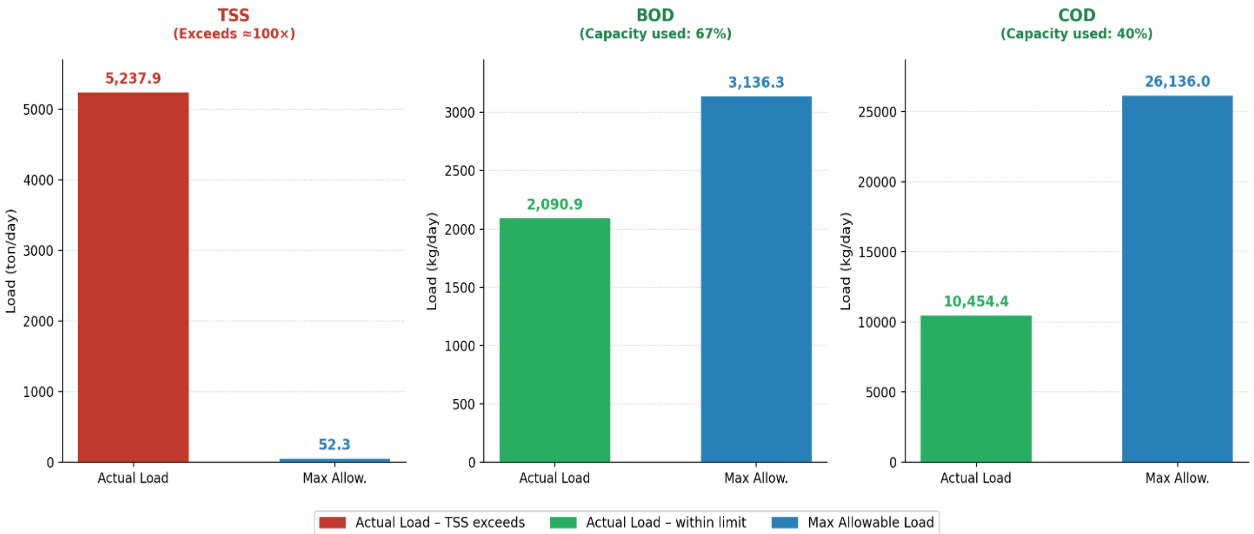

Figure 3. Comparison of actual pollution load and maximum allowable pollution load for TSS (ton/day), BOD (kg/day), balance approach (Equation 3) based on Class II standards under PP 22/2021. The TSS actual load (BPA = 5,237.9 ton/day) exceeded the maximum allowable load (BPM = 52.3 ton/day) by approximately 100-fold (TMDL = −5,185,641.6 kg/day), whereas BOD and COD remained within assimilative capacity at 67% and 40% utilization, respectively.

River Management Strategy Prioritization

AHP results from the four stakeholder panels are in Table 6. All pairwise comparison matrices achieved CR < 0.10 (overall CR = 0.076), indicating adequate judgment consistency. At the criteria level, government policy capacity received the highest weight (0.616), ahead of human resources (0.199), budget (0.121), and infrastructure (0.063). At the alternatives level, pollution load capacity determination ranked first (weight 0.341), followed by river classification (0.264), socialization and campaigns (0.184), supervision and monitoring (0.133), and law enforcement (0.078). The top-ranked alternatives share a common logic: both represent regulatory preconditions that stakeholders view as having to be met before operational interventions can be effective.

Table 6. Priority weights for five management strategy alternatives determined through AHP analysis incorporating input from four key stakeholder groups (government agency, PETI miners, formal mining company, and local community) in the Taluduyunu River watershed. Global priority weights were derived through multiplicative synthesis across all AHP hierarchy levels and are normalized to sum to 1.0. The consistency ratio (CR = 0.076 < 0.10) confirms acceptable judgment consistency. Higher weights indicate greater stakeholder consensus on implementation urgency.

No	Strategy alternative	Weight	Percentage (%)	Priority level
1	Pollution load capacity determination	0.341	34.1	Highest
2	River classification	0.264	26.4	Very high
3	Socialization & campaigns	0.184	18.4	Moderate
4	Supervision & monitoring	0.133	13.3	Moderate
5	Law enforcement	0.078	7.8	Lower

Discussion

Sediment Pollution as the Primary Threat to River Ecosystem Health

Across all four stations, organic indicators remained below detection; only TSS deviated substantially from Class II standards. That pattern points squarely at mechanical sediment disturbance as the source of impairment. At SR3, the confluence of five to seven simultaneously operating excavators with in-channel amalgamation processing produced a TSS reading of 21,000 mg/L, 420 times the regulatory threshold. For context, comparable ASGM rivers in Ghana's Oda catchment returned 438–1,755 mg/L [1], Cameroon's Lom River produced 47.6–471 mg/L [2] and Colombia's Suárez watershed 100–500 mg/L [21]. The Taluduyunu value exceeds all of these by at least an order of magnitude, placing this site among the most severely impacted ASGM rivers in the published regional literature. There are two excavators in the upstream section that appear to be in operation. The treated wastewater is not treated further, such as by being directed into a settling pond. The wastewater is discharged directly into the river.

Excavator operations produce high sediment loads through several reinforcing mechanisms. Removing riparian vegetation eliminates the bank-stabilising root network and the interception layer that would otherwise moderate overland runoff [14,15]. Direct excavation of the riverbed introduces unconsolidated material into the flow column without any retention. At SR3, the sustained simultaneous operation of multiple machines means the supply of sediment consistently outpaces the channel's transport capacity, driving progressive bed aggradation and bank widening. The partial TSS decrease from SR3 (21,000 mg/L) to SR4 (2,500 mg/L) reflects gravitational settling in the lower-gradient reach below the main mining zone, not a recovery of water quality; loads at SR4 still exceed TMDL by roughly 25-fold. Comparable mechanisms have been reported from artisanal mining sites in Ghana [1,22] and from ASGM-affected sediments in Gorontalo Province [7,8,23].

BOD/COD ratios of 0.20 were spatially uniform and essentially identical at the undisturbed headwater and at the peak mining station. That stability rules out organic waste as a variable of concern and directs management attention entirely toward sediment control. The same pattern has been reported from traditional gold mining reaches in Colombia, where TSS and turbidity dominated while organic parameters remained secondary [6,2]. Ecologically, TSS values in the range measured at SR2–SR4 cause direct physiological harm: gill abrasion, benthic habitat burial, and light restriction set in at concentrations above 1,000 mg/L [24], producing conditions that sensitive taxa cannot tolerate [25,26]. Work on the Osun River in Nigeria found near-complete disappearance of stress-sensitive macroinvertebrates from high-sediment reaches despite adequate dissolved oxygen [24]. PI scores confirmed the dominance of TSS across all mining-affected stations [20]. Heavy metals warrant secondary attention: zinc at SR3 reached 0.252 mg/L against a limit of 0.05 mg/L, and mercury, while below the acute toxicity threshold at 0.00007 mg/L, was detectable —

a finding that carries significance given well-documented bioaccumulation in aquatic food webs adjacent to ASGM sites [21]. Long-term mercury accumulation in river sediments has been documented at sites where active mining ceased years earlier, with contamination persisting for decades [27–29].

PP 22/2021 mandates pollution load carrying capacity determination as the regulatory basis for river classification and permitting. In practice, despite a 420-fold TSS exceedance at SR3, the Taluduyunu River has not been formally reclassified, TMDL values have not been operationalised into discharge permits, and ASGM operations have continued largely uninterrupted since the early 2010s**.** During the July–August 2023 field survey, no prohibition signs, monitoring posts, or signs of law enforcement presence were found along the SR2–SR3 mining zones. Residents interviewed stated that operations take place every day. This enforcement gap reflects jurisdictional fragmentation across national, provincial, and district authorities, which creates accountability deficits and stalls follow-through on monitoring findings [30]. The AHP results, TMDL determination (0.341) and river classification (0.264) as the two highest ranked priorities indicate that stakeholders have reached the same conclusion: the foundational regulatory instruments must be put in place before operational interventions can be designed or enforced. This constitutes what might be called a compliance-knowledge gap. Scientific evidence of severe impairment exists, but it has not yet been translated into enforceable regulatory action, with direct consequences for SDG 6 and SDG 15 implementation in Indonesia [11].

Indonesia's TMDL framework (Kepmen LH 110/2003—Ministerial Decree on Pollution Load Carrying Capacity Determination rests on the same mass balance logic as the US EPA's Total Maximum Daily Load (TMDL) process [18] and the EU Water Framework Directive [26]. All three set load thresholds keyed to designated-use standards. Where the frameworks diverge is in enforcement architecture: TMDL assigns binding wasteload allocations to individual permitted dischargers, a mechanism absent from TMDL; the Water Framework Directive (WFD) additionally incorporates hydromorphological quality elements not covered by PP 22/2021. The Taluduyunu case demonstrates the consequence of that gap: a defensible threshold (52,272 kg/day TSS) has been calculable for years, yet without a load-allocation mechanism, it carries no enforcement weight. Importing a TMDL-style allocation layer into the Indonesian regulatory structure would substantially strengthen pollution load carrying capacity as a management instrument [27].

The 100-fold TMDL exceedance recorded here points to a river that has moved beyond its geomorphological resilience threshold. A river's sediment budget the balance between incoming sediment supply, channel transport capacity, and depositional storage determines how much anthropogenic disturbance the system can absorb before structural change becomes self-reinforcing [28]. At measured discharge values of 1.9–6.0 m^3/s, the Taluduyunu's transport capacity falls far short of the PETI-introduced sediment flux. The result is progressive bed aggradation, hydraulic depth reduction, and lateral channel migration changes consistent with ASGM-driven channel destabilisation documented in West Africa [29] and Latin America [30]. Continued SR2–SR4 exceedance at these levels raises the possibility that the river is approaching an ecological tipping point from which natural recovery is no longer feasible without active intervention.

Management Implications and Strategic Priorities

Stakeholder priorities identified through AHP reinforce the regulatory sequencing argument: pollution load carrying capacity determination (34.1%) and river classification (26.4%) ranked ahead of community outreach, monitoring, and law enforcement. This ordering reflects stakeholder recognition that operational measures lack an enforceable baseline without prior pollution load carrying capacity establishment, a sequencing noted in the governance literature on informal mining regulation [31,32]. Moving beyond simple enforcement toward strategies that account for economic motivations and livelihood alternatives is also widely advocated [33]. The high weight assigned to government policy capacity (61.6%) signals stakeholder expectations that leadership from competent authorities is a prerequisite to any durable intervention [29,31]. The low weight for law enforcement (7.84%) is consistent with a stakeholder preference for participatory and technical pathways over punitive ones, a tendency observed in Indonesian ASGM governance contexts more broadly. Law enforcement against illegal miners has not been consistent. There have been several crackdowns, but it wasn't long before illegal mining resumed as usual. Synergy among the local government, the community, and business owners is needed to protect the Taluduyunu River [34–37].

The 3.4 million kg/day TSS load at SR3 represents an exceedance that cannot be addressed through monitoring alone. Restoring the river toward Class II compliance requires cutting inputs at the source: restricting excavator access to active channel sections, mandating sediment retention ponds at mine exits, and revegetating destabilised banks [34]. Those engineering controls need to be embedded in an institutional structure that allocates permissible loads to individual operators and tracks compliance over time — precisely what a formally operationalised TMDL framework would provide [35]. Given that PDAM Tirta Maleo draws from this same reach, the stakes extend directly to public health: service reliability and treatment costs for approximately 19,686 residents depend on reversing the current trajectory [38].

Conclusions

Excavator-based PETI in the upstream Taluduyunu River has pushed sediment loading to a level that overwhelms the river's assimilative capacity. TSS at SR3 reached 21,000 mg/L — 420 times the Class II standard under PP 22/2021, and total actual loads exceeded Pollution Load Carrying Capacity by roughly 100-fold. The Pollution Index placed SR3 in the heavily polluted category (PI = 10.01) and SR2 and SR4 in the moderately polluted range. BOD and COD were below detection at all stations, confirming physical sediment disruption as the sole meaningful degradation driver. Multi-stakeholder AHP ranked TMDL determination (weight 0.341) and river classification (0.264) as the two most urgent interventions. That ranking reflects a shared view: the regulatory preconditions must exist before operational controls can be enforced. Immediate sediment controls, excavator restrictions, retention structures, and riparian revegetation are urgently needed to protect the drinking water supply of approximately 19,686 Pohuwato Regency residents. These findings rest on a single dry-season snapshot with four stakeholders; wet-season data and a broader consultation would each strengthen the study. The combination TMDL and AHP approach used here may apply to other ASGM impacted watersheds in eastern Indonesia and comparable tropical settings where regulatory gaps constrain water quality management, in support of SDG 6 and SDG 15.

Author Contributions

SR: Methodology, Software, Data Curation, Investigation, Writing - Original Draft & Editing, Formal Analysis; **FGD**: Supervision, Conceptualization, Validation, Writing - Review & Editing; and **AFMZ**: Supervision, Conceptualization, Validation, Writing - Review & Editing.

AI Writing Statement

During the preparation of this work, the authors used Claude AI to parafrase the content. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Conflicts of interest

The authors declare no conflicts of interest.

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