

Supplementary

Part A. HRA Parameterization

Table S1. Habitat resilience parameterization

Habitat resilience attribute	Rating	DQ	Weight	E/C	Basis of assessment
Recovery time	2	1	3	C	Rating 2 reflects an expected recovery period of 1–10 years. The rating was assigned through structured expert judgment considering the persistence of anthropogenic disturbance and the expected reversibility of habitat impacts. The DQ score of 1 reflects the limited availability of direct, long-term empirical evidence on habitat recovery time, while the weight of 3 reflects the importance of recovery capacity in determining the consequence of habitat disturbance.

Rating instructions: Recovery time: 3 = >10 years, 2 = 1–10 years, 1 = <1 year, 0 = not scored.

Table S2. Stressor-specific HRA parameterization

Stressor	Criterion	Rating	DQ	Weight	E/C
Organic Pollution (BOD)	Frequency of disturbance	0	1	3	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	1	C
	Temporal overlap	2	3	1	E
	Management effectiveness	3	1	2	E
	Intensity	Spatially explicit layer (BOD.tif)	1	1	E
Chemical Pollution (COD)	Frequency of disturbance	0	1	3	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	1	C
	Temporal overlap	2	3	1	E
	Management effectiveness	3	1	2	E
	Intensity	Spatially explicit layer (COD.tif)	1	1	E
Land Use Pressure (Built-up)	Frequency of disturbance	2	1	2	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	2	C
	Temporal overlap	3	2	1	E
	Management effectiveness	3	1	2	E
	Intensity	Spatially explicit layer (Built_Up.tif)	1	1	E
River Fragmentation	Frequency of disturbance	2	2	3	C
	Change in affected area	2	1	1	C
	Change in water quality	1	1	2	C
	Temporal overlap	1	2	1	E
	Management effectiveness	2	1	2	E
	Intensity	3	1	1	E
Riparian Modification	Frequency of disturbance	2	2	3	C
	Change in affected area	2	2	1	C
	Change in water quality	2	1	1	C
	Temporal overlap	1	2	1	E

	Management effectiveness	2	1	2	E
	Intensity	2	1	1	E
Riverbank Modification	Frequency of disturbance	2	2	3	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	1	C
	Temporal overlap	1	2	1	E
	Management effectiveness	2	1	2	E
	Intensity	2	1	1	E
Sand Mining	Frequency of disturbance	2	2	2	C
	Change in affected area	2	1	2	C
	Change in water quality	2	1	2	C
	Temporal overlap	1	2	1	E
	Management effectiveness	3	2	2	E
	Intensity	1	1	1	E
Sediment Loading (TSS)	Frequency of disturbance	0	1	3	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	1	C
	Temporal overlap	2	3	1	E
	Management effectiveness	3	1	2	E
	Intensity	Spatially explicit layer (TSS.tif)	1	1	E
Aquatic Oxygen Stress (DO)	Frequency of disturbance	0	1	3	C
	Change in affected area	2	2	2	C
	Change in water quality	2	1	1	C
	Temporal overlap	2	3	1	E
	Management effectiveness	3	1	2	E
	Intensity	Spatially explicit layer (DO2.tif)	1	1	E

Notes: E = Exposure; C = Consequence; DQ = data-quality score. Criterion ratings were assigned using the predefined rating scheme in Supplementary Table S3. Ratings based on water-quality measurements and spatial datasets were informed by the available environmental data, whereas ratings for management effectiveness, recovery-related characteristics, and other criteria without direct quantitative observations were assigned using structured expert judgment. Data-quality scores reflected the availability, reliability, spatial coverage, and temporal representativeness of the supporting information. Criterion weights represented their relative importance within the HRA framework and were applied consistently across stressors. A rating of 0 indicates that the criterion was not scored because the required information was unavailable or not independently quantifiable. Spatially explicit intensity layers were used for BOD, COD, Built-up, TSS, and DO.

Table S3. HRA criterion rating scheme

Criterion	Rating 3	Rating 2	Rating 1	Rating 0
Frequency of disturbance	Annually or less often	Several times per year	Weekly or more often	Not scored
Change in affected area	50–100% loss	20–50% loss	0–20% loss	Not scored
Change in water quality	50–100% loss	20–50% loss	0–20% loss	Not scored
Temporal overlap	8–12 months yr ⁻¹	4–8 months yr ⁻¹	0–4 months yr ⁻¹	Not scored
Management effectiveness	Not effective	Somewhat effective	Very effective	Not scored
Intensity	High	Medium	Low	Not scored

Notes:

1. The rating scheme follows the standardized HRA Invest framework. Rating values are criterion-specific and are assigned according to the predefined categories for each assessment criterion.
2. Exposure/Consequence (E/C) and Data Quality (DQ) represent the exposure/consequence classification and confidence in the supporting data, respectively. Weight values represent the relative importance assigned to each criterion in the HRA calculation.
3. A rating of 0 indicates that the criterion was not scored because the relevant information was unavailable or the criterion was not applicable to the assessed stressor.
4. Spatially explicit criteria, including BOD, COD, built-up area, TSS, and DO, were assessed using geospatial datasets. Other criteria were assessed using predefined categorical ratings based on available observations, supporting datasets, environmental characteristics, and relevant scientific evidence.
5. For criteria assessed using expert judgment, the assigned ratings were based on the observed ecological and environmental conditions of the Biyonga River and its surrounding watershed. The basis for each stressor-specific rating is provided in Tables S1 and S2.
6. The HRA framework combines criterion ratings, data quality, and criterion weights to estimate the relative level of anthropogenic risk.

Part B. Field Data and Reference Standards

Table S4. Sampling locations and raw water-quality measurements

Sampling Point	Latitude (°)	Longitude (°)	Sampling date	DO (mg/L)	BOD (mg/L)	COD (mg/L)	TSS (mg/L)
T1	0.69239	122.98955	15-Jan-2026	6.8	2.7	13	30
T2	0.68582	122.98821	15-Jan-2026	6.5	2.7	16	36
T3	0.68497	122.98888	15-Jan-2026	6	3.5	19	46
T4	0.65208	122.98043	15-Jan-2026	5	6.1	29	72
T5	0.65914	122.98141	15-Jan-2026	4.6	7	33	85
T6	0.63147	122.97861	15-Jan-2026	5.1	5.3	28	70
T7	0.62070	122.97668	15-Jan-2026	5.5	4.5	25	58

Table S5. Class II water-quality standards used for comparisons

Parameters to be analyzed	Unit	Methods	Criteria (Class II standard)
Total suspended solids (TSS)	mg/L	SNI 6989.3:2019 (Gravimetric method)	≤ 50
Biochemical oxygen demand (BOD)	mg/L	SNI 6989.72:2009 (5-day BOD test)	≤ 3
Chemical oxygen demand (COD)	mg/L	SNI 6989.2:2009 (Titrimetric method)	≤ 25
Dissolved oxygen (DO)	mg/L	Measured in the field using a DO meter	≥ 4

Source: Government Regulation of the Republic of Indonesia No. 22 of 2021, Appendix VI (Class II water-quality standards).

Part C. Spatial Data and Model Implementation

Table S6. Data sources, GIS processing, and HRA implementation parameters.

Component	Data / Parameter	Source or Basis	Processing / Implementation
Water-quality data	DO, BOD, COD, and TSS	Field measurements from seven sampling locations	Ordinary kriging interpolation to generate spatial stressor layers
Land-use data	Built-up area and land-use/land-cover	ESRI LULC Dataset 2025 Zone 51N	Classification and spatial extraction
River-related features	River network, riverbank, and riparian areas	Field observations and spatial inventory	Digitization, spatial overlay, and buffer generation
Sand mining	Mining locations or observed extraction areas	Field observations and spatial inventory	Spatial digitization and classification
Spatial stressor layers	BOD, COD, DO, TSS, and built-up area	Derived from field and spatial datasets	Standardization and integration into the HRA framework
HRA criteria	Exposure and consequence criteria	Table S2 and Table S3	Criterion-specific ratings, data-quality scores, and weights
Habitat resilience	Recovery time	Literature supporting	Assigned according to the predefined rating scheme
Stressor buffer	100 m (baseline)	Model assumption	Applied around relevant stressor features
Distance decay	Not applied	Model assumption	No distance-decay function used in the baseline configuration
Risk aggregation	Multiplicative	HRA framework	Exposure and consequence combined to calculate cumulative risk

Sensitivity analysis	Buffer distances of 50, 100, 250, and 500 m	Alternative model configurations	Assessment of cumulative risk sensitivity
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Notes: DO = dissolved oxygen; BOD = biochemical oxygen demand; COD = chemical oxygen demand; TSS = total suspended solids; HRA = habitat risk assessment. Spatially explicit intensity layers were generated for BOD, COD, DO, TSS, and built-up areas, while categorical or vector-based information was used for the remaining stressors. Spatial input layers for all nine anthropogenic stressors, together with GIS processing materials and supporting implementation files, are available in the Zenodo repository: <https://doi.org/10.5281/zenodo.22844263>

Table S7. Kriging configuration and fitted variogram parameters.

Parameter	DO	BOD	COD	TSS
Kriging method	Ordinary Kriging	Ordinary Kriging	Ordinary Kriging	Ordinary Kriging
Variogram model	Spherical	Spherical	Spherical	Spherical
Search Neighborhood	Global neighborhood	Global neighborhood	Global neighborhood	Global neighborhood
Nugget	1.48×10^{-14}	1.35×10^{-12}	7.02×10^{-12}	2.71×10^{-14}
Partial sill	0.949	3.565	74.944	478.659
Full sill	0.949	3.565	74.944	478.659
Range (m)	5,144.58	4,025.92	5,436.35	4,608.37
Grid resolution (m)	5	5	5	5

Note: Variogram parameters were automatically fitted using PyKrig. The full sill represents the sum of the partial sill and nugget. A global search neighborhood was applied, meaning that all available sampling points were used during each kriging estimation. During LOOCV, six sampling points were used for each prediction.

Table S8. Point-wise observed and predicted values from leave-one-out cross-validation.

Variable	Point	Observed	Predicted	Error	Kriging Variance
DO	T1	6.80	6.177	-0.623	0.285
	T2	6.50	6.479	-0.021	0.212
	T3	6.00	6.036	0.036	0.502
	T4	5.00	4.948	-0.052	0.353
	T5	4.60	5.039	0.439	0.278
	T6	5.10	5.293	0.193	0.554
	T7	5.50	5.407	-0.093	0.712
BOD	T1	2.70	3.512	0.812	1.510
	T2	2.70	2.977	0.277	0.985
	T3	3.50	3.735	0.235	1.889
	T4	6.10	6.120	0.020	1.838
	T5	7.00	5.759	-1.241	1.262
	T6	5.30	4.923	-0.377	3.086
	T7	4.50	4.746	0.246	2.543
COD	T1	13.00	19.106	6.106	33.048
	T2	16.00	15.548	-0.452	14.657
	T3	19.00	20.065	1.065	33.448
	T4	29.00	29.584	0.584	28.584
	T5	33.00	28.431	-4.569	22.892
	T6	28.00	25.597	-2.403	59.163
	T7	25.00	25.193	0.193	58.353
TSS	T1	30.00	44.472	14.472	258.816
	T2	36.00	36.544	0.544	117.139
	T3	46.00	46.914	0.914	258.014
	T4	72.00	75.005	3.005	241.111

	T5	85.00	70.999	-14.000	169.454
	T6	70.00	62.824	-7.176	454.607
	T7	58.00	62.410	4.410	434.898

Part D. HRA Results and Sensitivity Analysis

Table S9. Overall habitat risk assessment results

Stressor	Exposure (E)	Consequence (C)	Risk (R)	High (%)	Medium (%)	Low (%)	None (%)
Sediment Loading	2.140	2.000	4.279	0.00	75.11	24.89	0.00
Organic Pollution	2.232	2.000	4.463	0.00	75.11	24.89	0.00
Chemical Pollution	2.057	2.000	4.115	0.00	75.11	24.89	0.00
Aquatic Oxygen Stress	2.035	2.000	4.070	0.00	75.11	24.89	0.00
Riparian Modification	1.074	1.228	2.149	0.00	61.39	0.00	38.61
Riverbank Modification	1.053	1.203	2.106	0.00	60.16	0.00	39.84
River Fragmentation	0.904	0.703	1.582	0.00	40.18	0.00	59.82
Land Use Pressure	0.390	0.453	0.779	0.00	9.94	12.73	77.34
Sand Mining	0.328	0.510	0.656	0.00	0.00	25.50	74.50
All Stressors	1.357	1.344	2.689	0.00	52.75	47.25	0.00

Note: E = exposure, C = consequence, R = habitat risk. Baseline scenario used a 100-m stressor buffer, no distance decay, and multiplicative risk aggregation.

Table S10. Sensitivity of cumulative habitat risk to buffer distance

Buffer distance	Mean Exposure	Mean Consequence	Mean Risk	High (%)	Medium (%)	Low (%)	None (%)
50 m	1.298	1.280	2.575	0.00	48.34	51.66	0.00
100 m	1.357	1.344	2.689	0.00	52.75	47.25	0.00
250 m	1.450	1.445	2.868	0.00	60.85	39.15	0.00
500 m	1.581	1.587	3.120	0.00	72.43	27.57	0.00

Part E. Supplementary Figures



Figure S1. Field photographs of seven sampling locations along the Biyonga River: (a) Sampling Point 1, upstream section; (b) Sampling Point 2; (c) Sampling Point 3; (d) Sampling Point 4; (e) Sampling Point 5; (f) Sampling Point 6; and (g) Sampling Point 7, downstream section.



Figure S2. Field water sampling and sample handling procedures in the Biyonga River: (a) water sampling, (b) in situ water quality measurement, (c) sample preparation and handling, and (d) collected water samples.



Figure S3. Laboratory procedures for water sample preparation and analysis: (a) preparation of water samples for laboratory analysis, (b) sample incubation, (c) sample handling and preparation, and (d) laboratory analysis using analytical instruments.