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Preliminary assessment of river ecosystem services in the volcanic area of Mount Merapi, Indonesia

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Abstract River ecosystem services (RES) are vulnerable to landscape changes mainly by volcanic eruptions. Therefore, this study aims to assess RES in the volcanic area which was affected by the major and minor eruptions of Mount Merapi, Indonesia. The RES referred to the regulating and supporting services of the Krasak River in Jogjakarta. The research involved collecting water and biodiversity samples from two distinct Merapi's hazard zones (KRB I and KRB II) along the river. Parameters related to regulating services, such as particulate, organic, and nutrient purification, biological control, as well as supporting services like primary productivity, were quantified. We conducted an analysis to understand how landscape conditions interacted with these parameters and employed the *t*-test to assess differences in RES between the two KRBs. Our findings revealed that the Krasak River exhibited a range of values, including 2.40–5.95 mg/l for Biological Oxygen Demand

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(BOD), 0.61–3.41 mg/l for nitrate, 0.02–0.11 mg/l for phosphate, 160–60,000 MPN/100 ml for coliform, and 156.3–937 µg/l for chlorophyll-A. These values demonstrated the river's capacity to perform both regulation and support services. However, certain segments showed variations in ecosystem services, possibly due to the presence of autochthonous matter from aquatic organisms and decomposing organic matters. This showed that volcanic eruption and landscape are closely linked with the water quality and aquatic biodiversity, which affect the ecosystem services.

Keywords Aquatic biodiversity · Ecosystem services · Krasak watershed · Merapi · River water quality

Introduction

Mount Merapi is an active volcano on Java Island that has minor and major eruptions with pyroclastic material spread to 10 rivers such as (1) Opak, (2) Bedog, (3) Krasak, (4) Code (or Boyong), (5) Gendol, (6) Winongo, (7) Gadjahwong, (8) Kuning, (9) Putih, and (10) Sempor (Gob et al. 2016). Despite its status as the most active volcano in Indonesia, the surrounding communities have special bonds that encourage them to stay. The latest eruption phase occurred on January 4, 2021, when magma supplies triggered a shallow volcanic earthquake 8 km below the earth's surface in October 2019 (BPPTKG 2021). This eruption caused a deformation of the mountain's flanks (Gomez et al. 2022) and produced Pyroclastic Density Currents (PDCs) 1–3 km from the summit (Thouret et al. 2020). The pyroclastic deposits distributed within the rivers that originate at Mount Merapi will turn into cold "lahar" (volcanic mudflow) during rainy seasons (Wibowo et al. 2015; Ville et al. 2015). Although the mount faces high risk, people still reside in the area because of several ecosystem services that support their lives (Chung and Kang 2013; Dede et al. 2023).

A combination of high rainfall in tropical areas and porous material deposits guarantees the abundance of surface and groundwater around Merapi (Ikhsan et al. 2019; Sekaranom et al. 2021). Especially for surface water, changes in the ecosystem services can be observed through river and reservoir water analysis. Previous observation has shown that Merapi's volcanic material is generally unconsolidated and easily erodible, which allows rainwater flows to transport into the river networks (Kusumawardani et al. 2017; Hapsari et al. 2020). Subsequently, a matrix mixture of rock, gravel, sand, dust, and water forms sediment loads in the rivers, which combine with erosion materials and anthropogenic activities from the surrounding land use. This surrounding landscape contains primary and secondary forests, as well as settlements, wet agricultural land, sand mining areas, fields, and plantations (Yudistira et al. 2020). The population growth and increased accessibility also trigger pressure on land, thereby contributing to changes in the water quantity and quality, biodiversity, and RES.

The combination of landscape changes, contaminants emergence, and human intervention is a determinant for the RES dynamics. RES expresses the ability of natural processes and components in a water body to provide direct or indirect adequate services for life needs. Moreover, the investigation of RES has garnered significant attention since the emergence of environmental degradation and the decline in biodiversity in freshwaters. For example, in Nenjiang River, China, it was discovered that reduced forest cover and wetlands for cultivation affect RES (water regulation and supply) by 4.62–14.34% since 1980 (Wang et al. 2015). Comprehending RES as observed in the Emscher River, Germany, is vital for optimal outcomes on environmental restoration such as water quality, biodiversity, climate regulation, and flood retention (Böck et al. 2018; Gerner et al. 2018). Hidayat et al. (2018) stated that erosion in the riverbank due to natural and anthropogenic activities can cause an increase in sediment loads, silt, and decrease water storage capacity in Brantas River, Indonesia. Material from the LUSI ('Lumpur Sidoarjo') mud volcano has been found to significantly contain high TSS and oxygen demand. The Porong River, which is the main tributary of the mud volcano, also contains heavy metals, but below the recommended standard (Krisnayanti and Agustawijaya 2014).

This study aims to assess RES in the volcanic area to understand how Merapi's eruption, landscape, and anthropogenic activities affect the regulating and supporting services. The study of volcanic eruptions and RES is a way to understand how volcanism correlates with the aquatic environment. These include particulate filtration, waste treatment, nutrient regulation, and biological control, as well as primary productivity, respectively. The RES changes occur due to landscape factors from volcanic eruptions and community behavior. A previous report has identified the river as a depository for mining materials such as sand and stone, these activities change ecosystem surrounding rivers around Mount Merapi (de Bélizal et al. 2013; Miller 2022). Therefore, the rivers in Merapi's landscape are not only a water provider but also a distribution route for cold lahar. Since RES changes to the surrounding dynamics, evaluating its effect in volcanic areas is necessary to support adequate policy development in the context of river usage and management (Burkhard et al. 2012).

Research method

Study area

This study examined RES in the Krasak watershed southwest of Mount Merapi. The watershed has an area of 35.48 km^2, which is divided into two provinces, namely Central Java and Yogyakarta as shown in Fig. 1. Furthermore, it has two permanent rivers upstreams with bird's feather-shaped, namely Bebeng and Krasak Rivers in the west and east section, respectively (Dede et al. 2022; Asdak 2023). The Krasak watershed is classified as a small landscape unit with an elongated shape from Mount Merapi to the southwest, located between 114 and 2871 m above sea level. The river flows from two sides, which begin to meet in the middle and become one flow downstream. Furthermore, it has an estuary at Kali Progo as the main flow of the river basin to the Indian Ocean, with a total flow length of 58.72 km and a centrifugal-radial pattern. The river is denser upstream than in the middle as well as downstream and the pattern encourages high water flow rates due to the significant elevation difference (Twidale 2004; Zhang and Guilbert 2013). Krasak water flow is a necessity for 28,081 inhabitants, for household

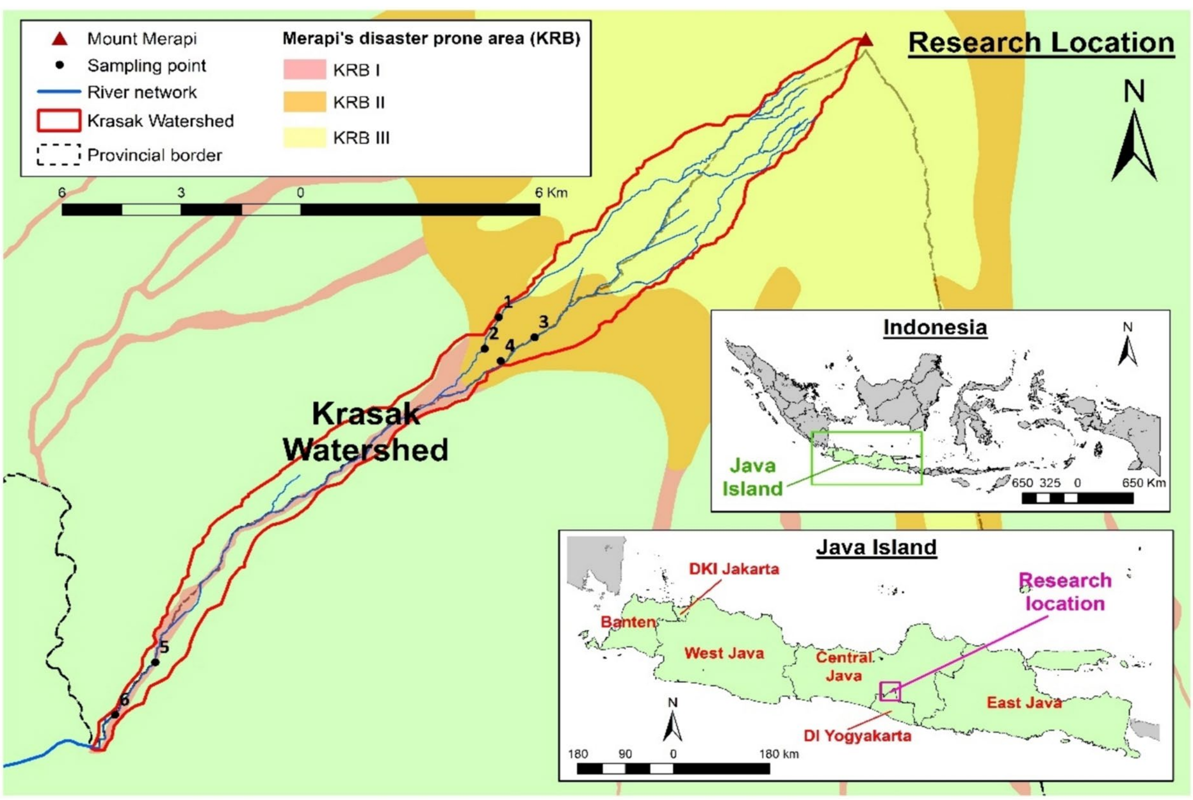

Fig. 1 The study location in the Krasak watershed shows the RES sampling distribution, where the green area is not the KRB Merapi zone. Sampling was only conducted in KRB I and II because of safety reasons during the Merapi's eruption

purposes and irrigating agricultural land. However, the volcanic activity and landscape dynamics of Mount Merapi will affect the river water quality, leading to changes in freshwater ecosystems and people's livelihoods. In Merapi's disasters, the watershed is classified into three disaster-prone areas (KRB) based on the National Agency for Disaster Countermeasure (BNPB).

Data acquisition

In this study, the evaluation of RES was carried out using the ecosystem service assessment from (Burkhard et al. 2012), with some modifications. The water and biodiversity sampling was concentrated at 6 points representing the different KRB statuses on the river network, we did sampling in dry seasons and chose the annual rivers where surface waters exist. The collection of water samples was carried out taking into account safety factors for researchers and following local government permits prohibiting sampling during the rainy season due to the strong and dangerous flow. Sample replication was conducted to obtain more credible data and avoid bias (Vaux et al. 2012; Storck et al. 2016; Danapriatna et al. 2023). The analysis procedures include components (parameters) identification, RES assessment, as well as the identification of interaction and landscape factors. The parameters observed included water quality, which includes total dissolved solids, total suspended solids, BOD, phosphate, nitrate, coliform, and chlorophyll-A as well as aquatic biodiversity, namely plankton, and macrobenthos. Specifically for plankton and macrobenthos, samples were analyzed using microscopic methods.

Data analysis

Water quality was evaluated through field measurements, which were also strengthened by laboratory analysis. Storet's method was employed to evaluate the water quality status and the pollution levels referring to The Decree of the Indonesian Minister of Environment 115/2003 (Hamzah et al. 2017; Hamzah and Priyadarshini 2019; Firmahaya and Piranti 2022). Meanwhile, biodiversity analysis uses three indices, namely (1) diversity, (2) uniformity, and (3) dominance as shown in Eqs. (1) and (2) (Sidomukti and Wardhana 2021). The enumeration of plankton and macrobenthos are categorized into different types based on their population density (individuals/L or individual per unit area). From this data, we can determine the number of each type (N) and the total number (S) present in the sample (Rosada and Sunardi 2021). The calculation of diversity indices was performed independently for each group (plankton and macrobenthos). The results obtained from Storet's method and biodiversity analysis require classification to know RES status with the criteria listed in Table 1. The state of RES was also evaluated for regulating services, including particulate filtration (TDS and TSS), waste treatment (BOD), nutrient regulation (nitrate and phosphate), biological control (coliform), and supporting services such as primary productivity. The status of each category was obtained by subtracting the value of the relevant parameter in the upstream part from the downstream at the same KRB. A negative value indicates that the river segment can eliminate the associated contaminants. Meanwhile, for supporting services, a negative value shows a decrease in primary productivity.

Table 1 Status of water quality and biodiversity analysis

Variable	Parameter	Information
Water quality	Physical, chemical, and biological	Storet's value, 0 (unpolluted), −1 to −10 (lightly polluted); −11 to −30 (medium polluted), more than or equal to −31 (heavily polluted)
Biodiversity	Diversity	H′ below 2.3026 (small diversity and low community stability), $2.3026 < H' < 6.9078$ (medium diversity and moderate community stability), H′ higher than 6.9078 (high diversity and high community stability)
	Uniformity	$J \approx 0$ (low uniformity and uneven distribution of individuals between species, there is a group of species dominate), $J \approx 1$ (high uniformity and illustrates that no species dominates, distribution of individuals between species is even)

$$H' = -\sum_{i=1}^{n} \left(\frac{n_i}{N}\right) \log \left(\frac{n_i}{N}\right) \quad (1)$$

$$E = \frac{H'}{H_{max}} \quad (2)$$

where H′ is the Shannon–Wiener's diversity, n_i represents individuals of i species, N is the individual total number of all species, E is the uniformity index, and H_{max} is the natural logarithm function of species.

The interaction between water quality and landscape conditions refers to Pearson's Correlation analysis. This method is useful to describe the relationship between variables, but it requires normality and data type (Sunardi et al. 2021; Nurbayani and Dede 2022; Widiawaty et al. 2022). Landscape factors that interact with water quality and biodiversity consist of the slope, elevation, distance from the caldera, vegetation greenness, river morphometrics (stream density), and distance from settlements. Slope and elevation data were based on DEMNAS (a digital elevation model from the Indonesian Government), while the radius analysis of settlements were obtained from the buffering method (Mulyadi et al. 2020; Dede et al. 2020; Susiati et al. 2022).Vegetation greenness was based on the normalized differences vegetation index (NDWI) from Landsat-8 OLI imagery (Dede and Widiawaty 2020). Moreover, stream density can be defined in the length of rivers in an area such as meter per km^2 or km per km^2. Furthermore, the *T*-Test was used to determine the differences in RES value among KRB zones (Widiawaty et al. 2020a). The significance of correlation coefficients and the *T*-Test was determined by a *p*-value of 0.05 at a 95% confidence level. However, H_0 for this study is 'volcanoes have an interaction with river ecosystem services' and workflow analysis as presented in Fig. 2. These methods were selected based on Shapiro–Wilk's normality test, indicating the *p*-value is 0.26 and exceeds 0.05 with a 95% confidence level.

Results and discussion

River water quality and pollution level

The river's physical characteristics reveal a TDS level of 254.40 mg/l and TS) at 18.43 mg/l. These concentrations decrease downstream, primarily due to sand and stone mining activities on the western upstream side, aligning with the findings from Tan and Rohasliney (2013). This study corroborates that mining materials contribute to higher particulate matter in water bodies, subsequently elevating TSS, TDS, and turbidity levels. In terms of chemical properties, the river have a BOD of 3.85 mg/l, along with nitrate levels of 1.67 mg/l and phosphate concentrations of 0.08 mg/l. These chemical parameters provide insight into the organic and nutrient content within the river's water. In areas close to agricultural and residential lands, these levels are higher compared to forests and shrubs (Dede et al. 2024). From biological aspects, the coliform and chlorophyll-A levels reached 13,395

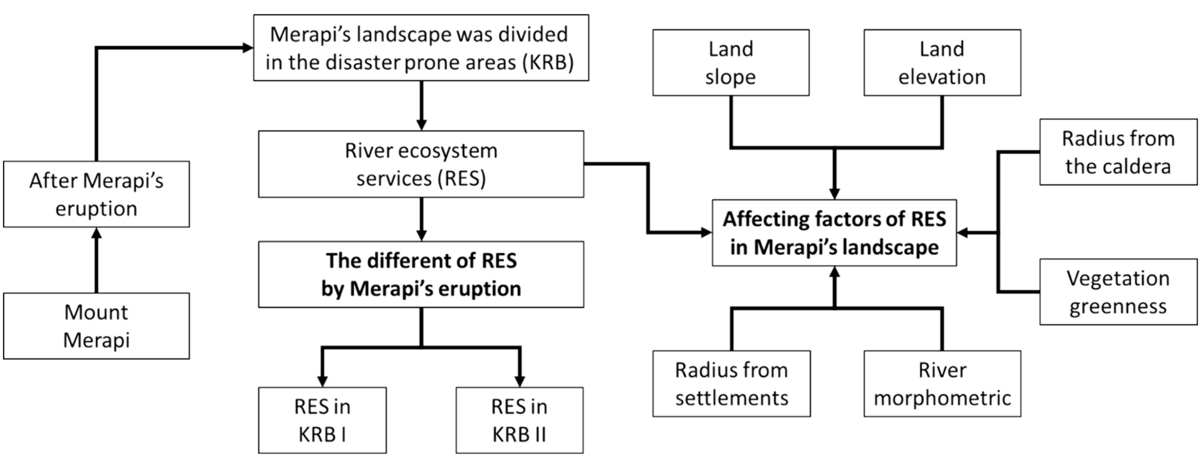

Fig. 2 Workflow analysis for RES in Mount Merapi

MPN/100 ml and 528.57 µg/l, respectively. Primary productivity tends to be higher upstream, including the coliform content on the west side. Details about water quality in 6 sampling stations are presented in Table 2.

Based on the three KRB, stations 3 and 4, as KRB II, have slightly better water quality as indicated by a relatively lower value of TSS, BOD, coliform, and phosphate, but high TDS and nitrate. Meanwhile, stations 1 and 2, as the other KRB II, experience worse water quality as shown by higher TDS, TSS, and BOD. The lower part, namely stations 5 and 6 which were part of KRB I, have the worst water indicators in coliform, nitrate, and phosphate. The pollutant characteristics represent the relevant situation and condition of the surrounding area. The upper area of the river is an active site of sand mining that fulfills the demand of the neighboring city and regencies. The sand exploitation has increased particulate matter in the river water, causing an elevation in the problems of high TDS. Furthermore, the highest impact of sand extraction occurred at stations 1 and 2, as indicated by the values of TDS and TSS. The lower stations have different characteristics of pollutants, namely high coliform, nitrate, and phosphate that represent the impacts of domestic and agricultural activities (Briciu et al. 2016a; Rachmadita et al. 2024).

The river water is categorized as 'heavily polluted' to 'not polluted' level based on the Storet's value as shown in Table 3. Referring to class 3, all sampling points are included in heavily polluted, meanwhile, when referring to class 4 they are in moderate to not polluted. From upstream to downstream, there is a longitudinal gradation in water quality, which is getting lower downstream. Between the two upstream areas at KRB II, specifically the west and east sides, there are differences in water quality and pressure on regulatory services. The low status downstream is a natural consequence of the accumulation of human activities along the watershed. Apart from erupting materials, several anthropogenic activities cause these water bodies to receive greater contaminants, therefore, the self-purification capacity was exceeded (Briciu et al. 2016b; Glińska-Lewczuk et al. 2016). At the upstream of the west side (sampling points 1 to 2), TSS and TDS loads are greater than the filtering capacity, leading to an increase in the river segment parameters. The loss of the ability to particulate filtration has implications for ecological processes in the waters such as inhibiting solar energy distribution, photosynthesis and reducing primary productivity. Aquatic animals that depend on visual vision, are very disturbed by excess particulates, which disrupt

Table 3 Storet's value for Krasak River based on the Decree of the Indonesian Minister of Environment 115/2003

Sampling ID	Zone	Storet's value	Pollution status
Quality standard (class 3)			
Stations 1 and 2	KRB II(a)	−50	Heavily polluted
Stations 3 and 4	KRB II(b)	−36	Heavily polluted
Stations 5 and 6	KRB (1)	−60	Heavily polluted
Quality standard (class 4)			
Stations 1 and 2	KRB II(a)	−6	Lightly polluted
Stations 3 and 4	KRB II(b)	0	Not polluted
Stations 5 and 6	KRB (1)	−24	Moderate polluted

Note Class 3 (water that can be used for freshwater fish farming, livestock, irrigation of crops, and other purposes that require water quality equivalent to these uses); Class 4 (water that can be used for irrigation of crops and other purposes that require water quality equivalent to those uses)

Table 2 Water quality of Krasak River

Sampling ID	Merapi's KRB	TDS (mg/l)	TSS (mg/l)	BOD (mg/l)	Nitrate (mg/l)	Phosphate (mg/l)	Coliform (MPN/100 ml)	Chlorophyll-A (µg/l)
1	KRB II	302.00	51.00	4.50	0.67	0.09	1,750	751.20
2	KRB II	253.50	32.50	5.95	1.42	0.07	17,500	937.90
3	KRB II	277.50	5.70	2.65	0.61	0.07	490	579.10
4	KRB II	224.00	5.10	2.40	2.72	0.02	160	456.00
5	KRB I	272.70	3.60	2.50	1.17	0.10	470	156.30
6	KRB I	196.70	12.70	5.10	3.41	0.11	60,000	290.90

Note KRB is the Merapi's hazard zones according to BNPB the ecosystem balance (Weber-Scannell and Duffy 2007; Chapman et al. 2017).

River biodiversity

In biodiversity, plankton is relatively more diverse than macrobenthos, the Shannon–Wiener's index value in the community at several locations is greater than 2.3026 and the community stability is moderate. At each sampling point, there were 31 to 50 species, as well as 52 phytoplankton, and 20 zooplankton. In uniformity, the plankton community showed a higher value. Merapi's eruption puts a certain pressure on the river ecosystem due to toxic pyroclastic materials and substrate changes in the water column (Juniah and Rahmi 2017). Although different conditions only occurred in the dominance, the significantly high macrobenthos value indicated the prevalence of certain species as presented in Table 4. Each sampling location contained different numbers of macrozoobenthos, ranging from 34 to 170 individuals, consisting of 18 species from 15 families. The lower diversity of macrobenthos also indicates that the eruption affects the bottom substrate of the waters. This support a report by Fazlutdinova et al. (2021) who discovered that invertebrate communities are vulnerable to changes in the composition of water columns and basic materials as their habitats.

State of the RES

The contaminant purification function of a river exists when the lower section contains a reduced contaminant load than the upper section. This showed that the Krasak River can treat several contaminant types such as particulate, organic, nutrient, and pathogen. However, some segments experienced disruption of the regulation functions as indicated by the elevated contaminants in the lower sites, namely high BOD, nitrate, and coliform in KRB II. The increase in BOD and other organic contaminant indicators can be from autochthonous sources, while the overload of organic waste was beyond the river water's ability to decompose. A similar phenomenon occurred in the ability of nutrient regulation in water, especially nitrate, which decreased and caused a surplus of nitrate, thereby triggering algae blooms and disrupting ecological integrity (Weiss et al. 2016). Disruption also occurred in the biological control capacity as indicated by the total coliforms in each segment, except for KRB II segment b. According to Cabral (2010) and Pandey et al. (2014), changes in any physical, chemical, and biological environment play a major role in determining the pathogenic microorganisms. Supporting services on the Krasak river are relatively good, as presented by the primary productivity, except in KRB II(b) from Table 5. The primary productivity maintains biomass and energy supply sufficient to retain the supporting services of the river (Widiawaty et al. 2020b).

Landscape indicators

Merapi's eruptions and landscape changes have a potential relationship with water quality and aquatic biodiversity as the main variables of RES in Fig. 3 and Table 6. It was also discovered in Table 7 that the Krasak river flows close to settlements in around less than 200 m. In the stream density, the lower value shows the small debits supply from the periodic rivers along the main river. Besides densely stream upstream, the river flow is located at steeper slopes than the middle and downstream. Vegetation greenness at six sampling points is classified as highly dense according to the NDVI value of more than 0.60 (Yacouba et al. 2010). Although the vegetation

Table 4 Plankton and macrobenthos biodiversity of Krasak River

Sampling ID	Merapi's KRB	H′ plankton	E plankton	H′ macrobenthos	E macrobenthos
1	KRB II	2.95	0.80	1.43	0.28
2	KRB II	1.60	0.45	1.26	0.27
3	KRB II	2.60	0.76	2.03	0.52
4	KRB II	2.83	0.80	1.58	0.45
5	KRB I	2.99	0.76	1.48	0.35
6	KRB I	2.19	0.59	1.28	0.26

Note H′ is the Shannon–Wiener's diversity and E is the uniformity index

Table 5 State of ES in Krasak River

Ecosystem services	Parameter	KRB II(a) Sampling ID 1 to 2	KRB II(b) Sampling ID 3 to 4	KRB I Sampling ID 5 to 6
Regulating services				
Particulate filtration	TDS (mg/l)	−48.50	−53.50	−76.00
	TSS (mg/l)	−18.50	−0.65	9.03
Waste treatment	BOD (mg/l)	1.45	−0.25	2.60
Nutrient regulation	Nitrate (mg/l)	0.75	2.11	2.24
	Phosphate (mg/l)	−0.02	−0.05	0.01
Biological control	Coliform (MPN/100 ml)	15,750	−330	59,530
Supporting services				
Primary productivity	Chlorophyll-A (μg/L)	186.70	−123.10	134.60

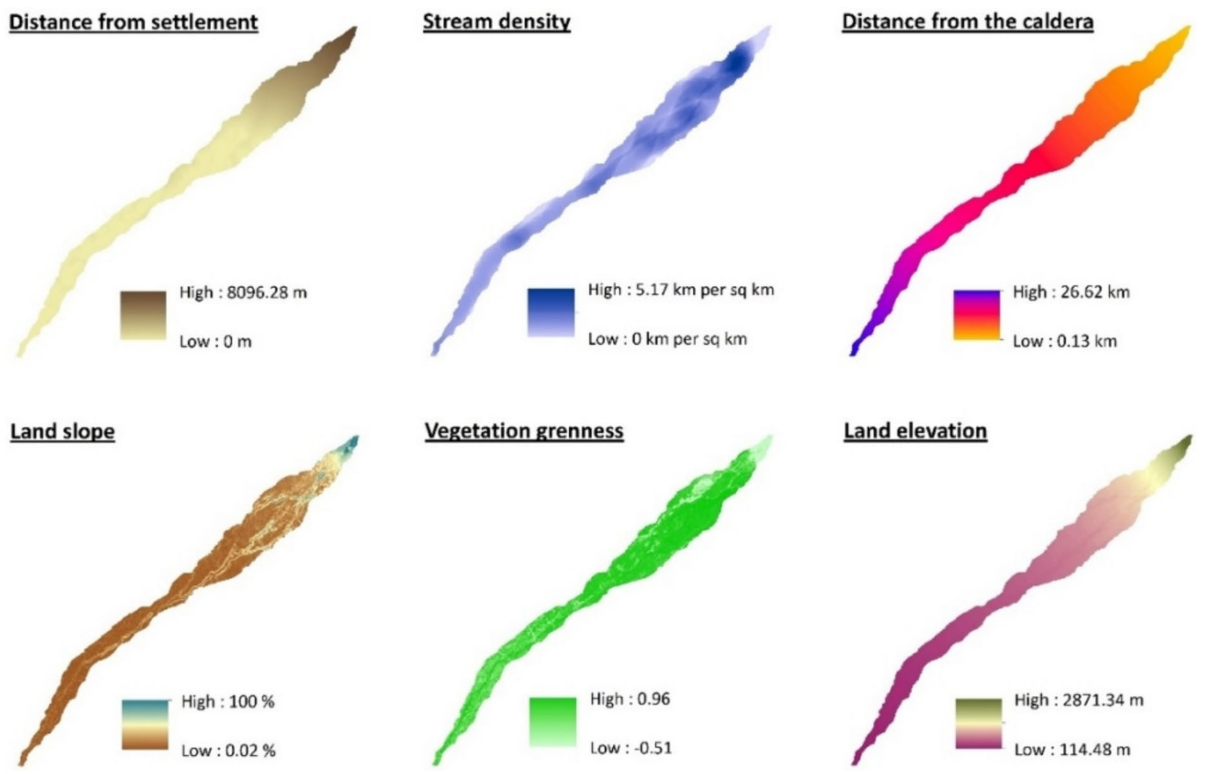

Fig. 3 Landscape parameters in Krasak Watershed

is being threatened by anthropogenic activities and the built-up area in the downstream riverbanks. Since the land slopes are not too steep and calm water flow, people can easily cross the river. Several rapids were not found in the river and the sunlight was able to reach the bottom of the water. Meanwhile, land elevation and slope only changed significantly in an area less than 5 km from Merapi's peak, which rarely interacts directly with people.

River water quality-landscape indicator relation

The correlation shows that water quality and aquatic biodiversity have significant interaction with all

Table 6 Landscape factors value in Krasak Watershed

Sampling ID	Merapi's KRB	Distance from settlements (m)	Stream density (km/km^2)	Distance from the caldera (m)	Land slope (%)	Vegetation greenness	Land elevation (m)
1	KRB II	189.74	1.04	11,556.10	12.24	0.75	568.14
2	KRB II	84.85	1.61	12,350.50	20.45	0.79	527.58
3	KRB II	42.43	1.08	11,208.10	4.47	0.82	565.81
4	KRB II	42.43	1.46	12,260.10	29.82	0.85	525.37
5	KRB I	30.00	1.08	23,924.40	5.59	0.68	177.80
6	KRB I	0.00	1.32	25,589.00	8.44	0.79	149.50

Table 7 Correlation between landscape factors and water quality

Parameter	Distance from settlements	Stream density	Distance from the caldera	Land slope	Vegetation greenness	Land elevation
TDS	0.71	−0.61	−0.48	−0.33	−0.44	0.48
TSS	0.90**	−0.01	−0.40	0.11	−0.16	0.43
BOD	0.29	0.46	0.04	0.07	0.00	−0.01
Nitrate	−0.59	0.53	0.50	0.38	0.35	−0.50
Phosphate	0.00	−0.47	0.66	−0.81*	−0.70	−0.64
Coliform	−0.42	0.31	0.62	−0.16	0.10	−0.59
Chlorophyll-A	0.67	0.37	−0.79*	0.35	0.34	0.80*
H′ plankton	0.17	−0.74*	0.03	−0.17	−0.31	−0.03
E plankton	0.20	−0.71	−0.16	−0.10	−0.11	0.16
D plankton	0.71	−0.45	−0.58	0.19	0.12	0.60
H′ macrobenthos	−0.13	−0.47	−0.42	−0.27	0.33	0.41
E macrobenthos	−0.29	−0.23	−0.40	0.01	0.46	0.38
D macrobenthos	0.81*	−0.31	−0.13	−0.09	−0.28	0.17

** p-value < 0.001 and * p-value < 0.05 with 95% confidence level

landscape factors, except vegetation density as presented in Table 7. TSS and macrobenthos dominance index have a significant positive correlation with settlements, while plankton diversity is inversely proportional to the stream density. Settlements provide a significant supply of TSS, which came from domestic waste and high run-off (Ekka et al. 2020). Denser flow provides a high-current supply and easily washed away the plankton community (Zhao et al. 2015). Phosphate is also negatively correlated with the slope, moreover, phosphate and nitrate are nutrients that support and increase primary productivity.

At each sample point and segment, there are changes in water quality and biodiversity along with Krasak flow. Based on the statistical analysis in Table 8, there is no significant difference in RES for each segment. A pairwise comparison between the three segments shows that the t-value ranged from −1.005 to 1.021. This indicated that the Krasak river requires rehabilitation efforts to maintain its RES. The statistical results also showed that several ecosystem services declined from the upstream, causing accumulative impacts in the middle and downstream. Furthermore, dozens of Sabo Dams

Table 8 The results of RES

Pair	t-value	p-value
KRB II(a)–KRB II(b)	1.021	0.346
KRB II(a)–KRB I	−0.999	0.357
KRB II(b)–KRB I	−1.005	0.354

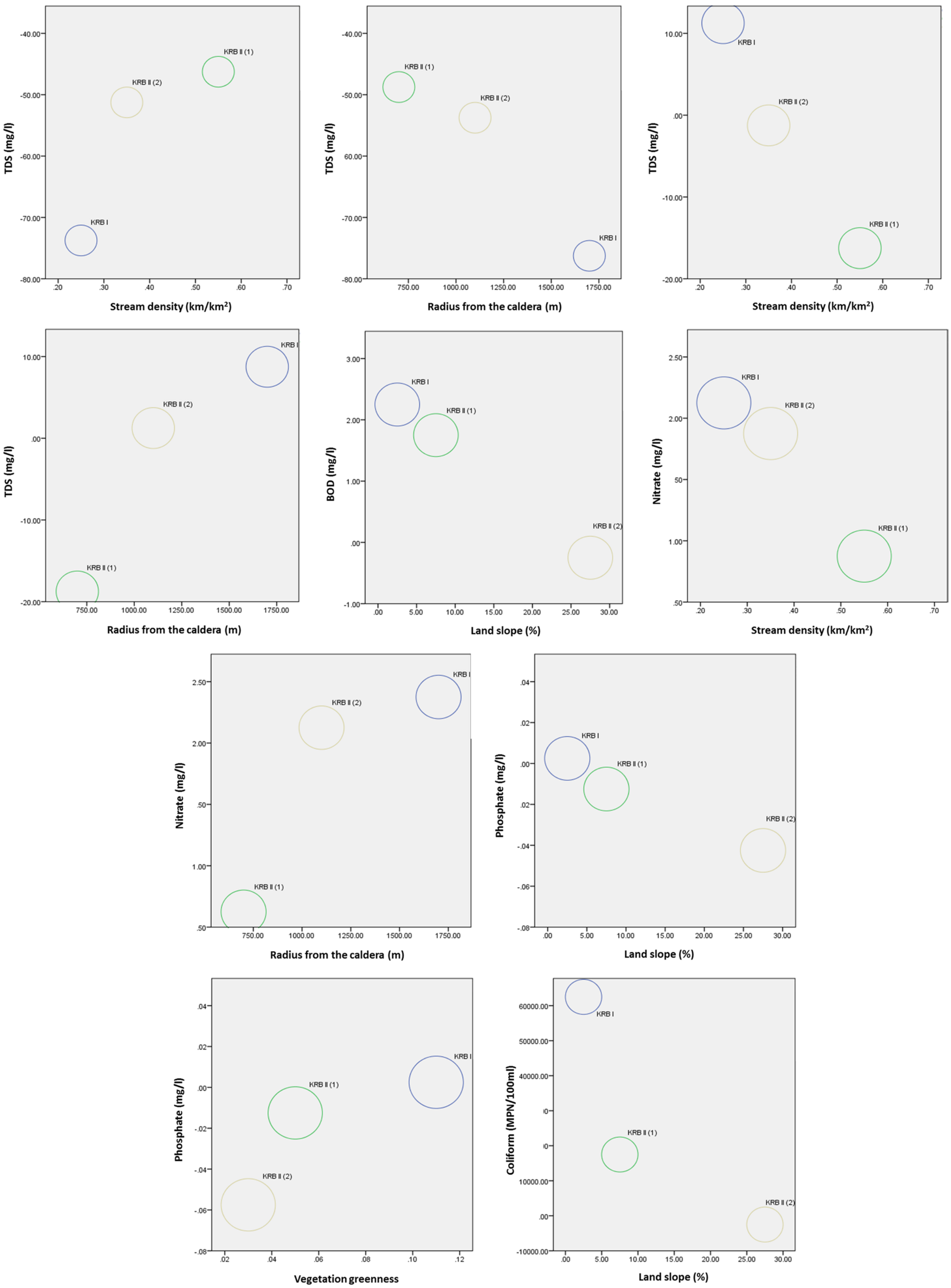

Fig. 4 Potential role of landscape factors on RES

are still ineffective without being accompanied by community-based environmental conservation and rehabilitation (Wisoyo 2015; Purwantoro et al. 2021). The Sabo Dam is only effective as contaminants filter from upstream and not from the landscape around the Krasak river.

RES-landscape indicator relation

The parameter of RES has a significant correlation with the elevation and distance from Merapi's caldera. At the upstream, it has relatively little interaction with human activities, causing higher chlorophyll-A levels. As presented in Fig. 4, landscape factors can affect several ecosystem services such as particulate filtration (TDS), waste treatment (BOD), nutrient regulation (nitrates and phosphates), and biological control (coliform). The positive interactions are indicated in the stream density and radius from the caldera into TDS, nitrate, and vegetation greenness to phosphate. A previous investigation stated that substrate and colloid levels tend to be higher in calm waters, besides the high supply of sediment from other waterways (Sunardi et al. 2022). High nitrate and phosphate in rivers far from the caldera indicate that the supply is more dominant from human activities, especially from agrochemicals usage. Hence, phosphate levels can be increased even though the surrounding area is agricultural land and plantations (Mulyadi et al. 2023). This information needs further verification by involving many observation stations in the Merapi's freshwater environment, including revealing the existing negative interactions.

Conclusion

The Merapi's eruptions are the main agent of landscape change, besides anthropogenic activities that natural resources. Based on the results, the water quality of the Krasak watershed is in class 3 and 4 uses according to the quality standard. It was also discovered that the disturbances to water quality are not only caused by eruptive materials but are more dominant by intensive sand and stone mining upstream. Plankton species exhibit greater diversity compared to macrobenthos, with the latter group also displaying dominance (abundance) throughout the Krasak river. Moreover, RES which include functions like particulate filtration, waste treatment, nutrient regulation, biological control, and primary productivity, experience more disruption in the upstream areas as opposed to downstream regions. Volcanic landscapes (elevation and distance from Merapi's caldera) play a crucial role in influencing water quality and aquatic biodiversity, although they have a limited impact on vegetation greenness. Notably, the changes in RES within the Krasak river were relatively insignificant, as water quality and aquatic biodiversity appear to decrease consistently along the river's course. The government, together with the community and related stakeholders, should include RES as an aspect affected by Merapi's volcanic disaster. These efforts should be realized by integrating them into development plans at the national, provincial, and district/city levels in the KRB areas. Therefore, further investigation is recommended by involving more sampling stations and water quality parameters such as heavy metal contents, oil spills, and nekton organisms.

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Data Availability Data will be made available on reasonable request.

Declarations

Conflict of Interest The authors declare there is no conflict of interest.

Ethical Statement Not applicable.

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