Biological Regulation of Ecosystem Services under Water Quality Pressure at Trisula waterfall

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Abstract. Waterfall ecosystems provide critical provisioning services, including drinking water, irrigation, and ecotourism depends on the physicochemical conditions of the water and the ability of biological regulation. This study aimed to assess water quality at Trisula waterfall and its implications for the sustainability of ecosystem services. Sampling was conducted at three stations (upper river, waterfall point, and lower river) during the dry season. Physicochemical parameters analyzed included discharge, pH, dissolved oxygen, nutrients, turbidity, total dissolved solids, and organic matter. Benthic macroinvertebrates were also used as bioindicators of ecosystem regulation. Data were analyzed using ANOVA, Prati's Implicit Index, and biotic indices. The results showed that water discharge ranged from 0.33–1.22 L s^{-1}. The concentrations of nitrate (6.83–7.63 mg L^{-1}) and orthophosphate (0.23–0.27 mg L^{-1}) were relatively high due to agricultural activities, but still below national quality standards. Biological indicators showed higher diversity and dominance of sensitive taxa at the waterfall location, reflecting better ecosystem regulation capabilities. The Prati Index value (1.56–1.70) indicated that the water quality was considered good, but not yet suitable for direct consumption. Integrated management through nutrient control, riparian restoration, and biological monitoring is necessary to maintain the sustainability of ecosystem services and the tourism value of Trisula Waterfall.

Keywords: Ecosystem services; benthic macroinvertebrates; biological regulation; water quality; waterfalls.

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1 Introduction

Ecosystem services (provisioning, regulating, and cultural) are critical for human well-being and sustainability [1]. Ecosystems provide numerous services that contribute to the needs of food, clean water, and even genetic material. Ecosystems also help regulate climate, water flow, and even pollination. Culturally, humans can utilize ecosystems for spiritual, recreational, and educational activities. Other ecosystem services also benefit humans in disaster mitigation. The sustainability of these services is strongly influenced by the interaction between physicochemical conditions and biological regulation within ecosystems.

Waterfall ecosystems provide critical provisioning services, including drinking water, irrigation, and ecotourism [2]. However, these services are increasingly threatened by human activities such as agriculture and land-use change. Dependence on aquatic ecosystem services increases with human population growth [3]. This dependence puts pressure on ecosystems, particularly agriculture and land use. Meanwhile, the availability and quality of drinking water tends to decline due to intensification of agricultural activity and land use change.

Human activities (agriculture, tourism) can alter water quality, affecting ecosystem functions [2]. These disturbances often lead to changes in the structure of aquatic fauna communities, particularly benthic organisms that play a crucial role in nutrient cycling and energy flow [3]. Changes in aquatic community composition can reduce ecosystem resilience and weaken regulatory services that control nutrient enrichment and organic pollution. Land-use changes also affect hydrological processes that regulate water flow and flood dynamics.

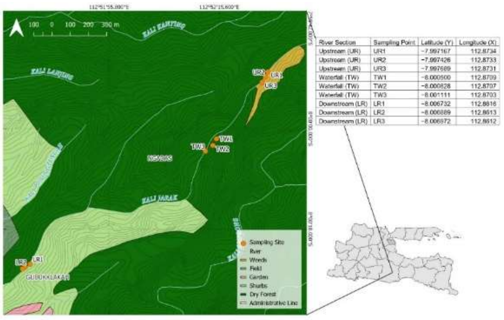
Trisula waterfall is a potential area managed by Bromo Tengger Semeru National Park (TNBTS). Trisula waterfall serves as a habitat for several raptors, including members of the Accipitridae, Falconidae, and Pandionidae families. Eight raptor species have been identified at Trisula waterfall [4]. The Trisula waterfall area supports diverse understory vegetation with medicinal potential, comprising 18 species from several plant families. Despite some land-use disturbances, the area is classified as a disturbed secondary forest with high biodiversity. Carbon stocks remain relatively high due to protected forest stands, and assessments using the Hemeroby and Naturalness Indices indicate low levels of human disturbance without significant habitat fragmentation [5]. The problem encountered is water runoff from surrounding villages entering the Trisula waterfall's water body, potentially polluting the area. Thus, Trisula waterfall is categorized as quasi-natural to sub-natural.

Previous research has revealed the ecological importance of Trisula Waterfall, but integrated studies linking water quality, biological regulation, and ecosystem services are limited. The presence of upstream villages, such as Ngadas and Jarak Ijo, with intensive agricultural activities, has the potential to degrade water quality through agricultural runoff. Therefore, integrating physicochemical parameters and benthic bioindicators is necessary to accurately assess ecosystem health. This study aims to evaluate water quality and ecosystem services and formulate recommendations for sustainable management.

2 Research Methodology

Study Area

This research was conducted at Trisula waterfall, located in Ngadas Village, Poncokusumo District, Malang Regency, East Java, Indonesia (Figure 1). This site is managed by the Trisula waterfall National Park Management Resort under the Bromo Tengger Semeru National Park. The waterfall is located at an altitude of approximately 1,400 meters above sea level (masl). Sampling was carried out at three river sections representing longitudinal variation: upstream (UR), waterfall area (TW), and downstream (LR). Each section consists of three sampling points as replicates. The upstream and downstream areas are influenced by surrounding agricultural activities, particularly vegetable cultivation, which may affect water quality.



River Section	Sampling Point	Latitude (Y)	Longitude (X)
Upstream (UR)	UR1	−7.997167	112.8734
Upstream (UR)	UR2	−7.997426	112.8733
Upstream (UR)	UR3	−7.997689	112.8731
Waterfall (TW)	TW1	−8.000500	112.8709
Waterfall (TW)	TW2	−8.000828	112.8707
Waterfall (TW)	TW3	−8.001111	112.8703
Downstream (LR)	LR1	−8.006732	112.8616
Downstream (LR)	LR2	−8.006889	112.8613
Downstream (LR)	LR3	−8.006972	112.8612

Fig. 1. Sampling site of Trisula waterfall.

Sampling Design

Sampling was conducted from February to August 2017, with three replicates in each river section (upstream, waterfall, and downstream). The dry season was intentionally omitted to avoid ambiguity regarding seasonal rainfall variability during the sampling period. At each station, physical, chemical, and organic water quality parameters were measured. These parameters included discharge and current velocity, temperature, pH, dissolved oxygen (DO), conductivity, bicarbonate, total dissolved solids (TDS), turbidity, nitrate, orthophosphate, and total organic matter (TOM). The selected parameters were intended to represent the hydrological characteristics, nutrient status, and organic inputs that influence aquatic ecosystem processes [6].

Measured Parameters

The parameters measured are classified into physical (discharge, current velocity, temperature, turbidity, TDS), chemical (pH, DO, bicarbonate, conductivity, nitrate, orthophosphate), and organic (TOM). Physical parameters describe hydrological dynamics and habitat structure, chemical parameters reflect water chemistry and nutrient availability, while organic parameters represent organic inputs that influence oxygen demand and biological processes. Together, these parameters provide a comprehensive description of water quality conditions and their potential impact on ecosystem services.

Benthic Macroinvertebrate Bioindicators

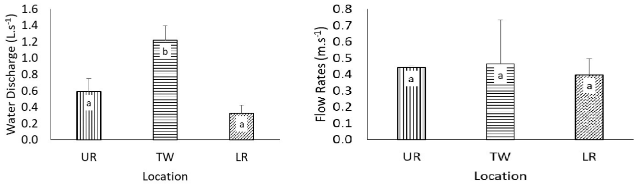
Ecosystem service regulation was assessed using benthic macroinvertebrates as bioindicators of water quality. Sampling was conducted in three river sections: upstream, waterfall area, and downstream. In each section, benthic organisms were collected using a Surber net (sampling area 20 × 50 cm; mesh size 250 µm) from the midstream with rocky, gravelly, and sandy substrates, and using a hand net along the riverbanks dominated by riparian vegetation. Sampling was conducted in triplicate in each river section to obtain a minimum of 100 individuals per section. Collected specimens were preserved in 70% alcohol and identified in the laboratory using a stereomicroscope at 40× magnification. Benthic community analysis included abundance, frequency, importance value index (IVI), and Shannon–Wiener diversity index (H’). Water quality was further assessed using the Family Biotic Index (FBI) and the Hilsenhoff Biotic Index (HBI) based on the tolerance values of benthic taxa. The index values are interpreted following the classification proposed by Mandaville to determine the water quality status and the level of organic pollution as indicators of regulating ecosystem services [7].

Data Analysis

Statistical analysis was performed by first testing data assumptions using normality and homogeneity tests. Differences in water quality parameters between river sections were analyzed using analysis of variance (ANOVA), followed by the Tukey Honestly Significant Difference (HSD) test for pairwise comparisons. All statistical analyses were conducted using Paleontological Statistics (PAST) software version 5.2.1. An integrated water quality assessment was conducted using the Prati Implicit Pollution Index, which combines physical, chemical, and organic parameters. The results were compared with national water quality standards based on Government Regulation No. 82 of 2001 concerning Water Quality Management. Water quality status was interpreted according to the following classes:
Class I : water suitable for direct drinking water sources;
Class II : water suitable for water recreation, freshwater aquaculture, and agriculture;
Class III : water suitable for freshwater aquaculture, agriculture, and livestock;
Class IV : water suitable for industrial purposes and other uses requiring lower water quality standards.

3 Results and Discussions

Flow and Discharge



Note: Upper River (UR); Trisula Waterfall (TW); Lower River (LR)

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Fig. 2. Average water discharge and flow rate at each station. (The same letter indicates no significant difference between areas at the $\alpha = 0.05$ level, ANOVA–Tukey HSD).

Water discharge reflects the volume of water flowing per unit time and varies spatially due to differences in channel morphology and flow velocity. Average discharge ranged from 0.33 to 1.22 L s^{-1} (Figure 2). The highest discharge was recorded at the waterfall (1.22 L s^{-1}), followed by the upstream section (0.58 L s^{-1}), and the lowest downstream section (0.33 L s^{-1}). These differences were statistically significant (ANOVA–Tukey HSD, $\alpha = 0.05$).

The higher discharge at the waterfall is associated with additional inflow and increased hydraulic pressure, while the decrease in discharge downstream is likely influenced by agricultural water withdrawals and reduced riparian vegetation cover. Despite the decreased discharge downstream, water availability for local communities remains sufficient due to the presence of alternative water sources. Discharge variations influence sediment transport, dilution capacity, and erosion risk, thus affecting nutrient dynamics and ecosystem regulation processes [8]. Despite fluctuations in water discharge, the relatively high diversity of benthic macroinvertebrates indicates that regulatory ecosystem functions, such as nutrient retention and pollution mitigation, remain functional [9].

Nutrients (Nitrate and Phosphate)

Nitrate concentrations ranged from 6.83–7.63 mg L^{-1}, while orthophosphate concentrations ranged from 0.23–0.27 mg L^{-1} at all stations (Figure 3). Although nitrate levels remain below the Indonesian drinking water threshold (<10 mg L^{-1}), orthophosphate concentrations are relatively high compared to natural background levels.

The increase in nutrient concentrations is primarily due to the intensification of agricultural activities in the Jarak Ijo and Ngadas areas, where synthetic fertilizers are frequently applied. Nutrient enrichment poses potential risks to eutrophication and ecological sustainability, especially under low or stagnant flow conditions [6]. Increased nitrate and phosphate concentrations can benefit tolerant benthic taxa while reducing sensitive species, thereby altering community structure. Consequently, nutrient management through sustainable agricultural practices is crucial for maintaining water quality and ecosystem services in the Trisula waterfall area.

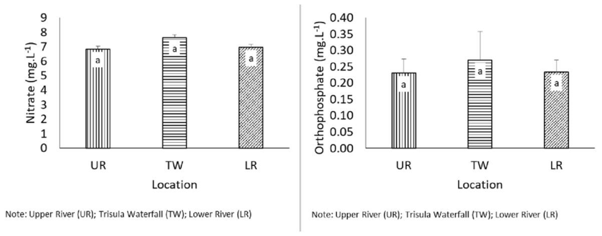


Fig. 3. Average nitrate and phosphate levels at each station. (The same letter indicates no significant difference between areas at the α = 0.05 level, ANOVA–Tukey HSD).

Organic Matter and Water Clarity

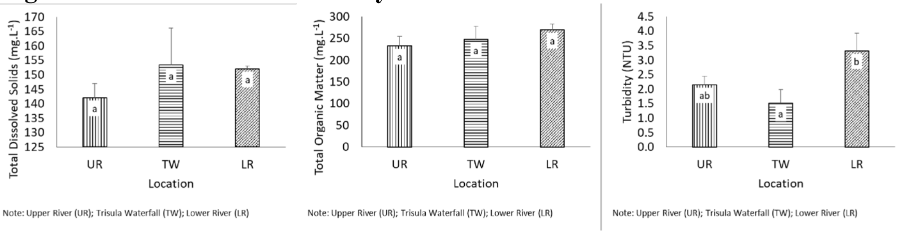


Fig. 4. Average TDS, TOM, and turbidity at each station. (The same letter indicates no significant difference between areas at the α = 0.05 level, ANOVA–Tukey HSD).

Total dissolved solids (TDS), total organic matter (TOM), and turbidity showed values of 142–153 mg L⁻¹, 232–269 mg L⁻¹, and 1.52–3.32 NTU, respectively (Figure 4). TDS values did not vary significantly between stations, indicating low dissolved ion concentrations, which are generally favorable for aquatic biota. In contrast, TOM and turbidity showed spatial variation. The increase in TOM was caused by organic input from vegetation debris, re-suspended sediment, and hydraulic pressure at the waterfall. Increased turbidity, caused by inorganic particles (sediment derived from erosion) and organics, can block light penetration and increase microbial oxygen demand. Riverbank vegetation plays a key role in reducing erosion and regulating organic matter input [10]. Therefore, maintaining riverbank buffers is crucial to minimize organic pollution and maintain ecological sustainability and tourism value.

General Water Quality

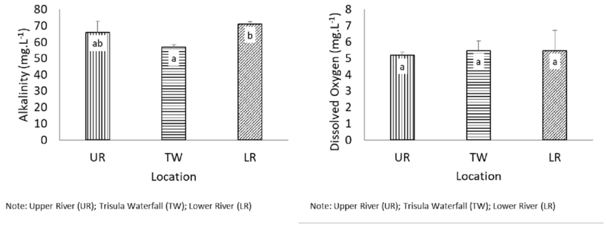


Fig. 5. Average alkalinity and dissolved oxygen at each station. (The same letter indicates no significant difference between areas at the α = 0.05 level, ANOVA–Tukey HSD).

Water quality is generally determined by measuring bicarbonate, dissolved oxygen, pH, temperature, and conductivity. The average bicarbonate level ranges from 56.8–70.9 mg L^{-1} (Figure 5). This value shows significant differences between locations: in the upper river it is ±65.9 mg L^{-1}, decreasing to ±56.8 mg L^{-1} at the waterfall, then increasing to ±70.9 mg L^{-1} in the lower river. This variation is influenced by the presence of rocks as a natural source of alkalinity and ion input from agricultural fertilizers that increase alkalinity through reaction with carbonate. Agricultural land conversion increases alkalinity values, while good riparian habitats tend to suppress them. In order to preserve pH stability and shield aquatic life from the damaging effects of acid rain, alkalinity is essential [6]. Controlling N and P from agricultural activities, as well as riparian conservation, is necessary to maintain the stability of this parameter.

Dissolved oxygen concentrations ranged from 5.17–5.47 mg L^{-1} with no significant differences among stations, meeting Class II but not Class I standards (PP No. 82/2001). Reduced DO is associated with organic inputs and limited riparian vegetation, supported by the presence of tolerant taxa such as Tubificidae. pH values (7.38–7.46) remained within Classes I–III, although a slight downstream decrease indicates increasing acidity. Water temperature was relatively low (15.8–18.9 °C) due to highland conditions and riparian canopy cover. Maintaining riparian vegetation is essential for regulating temperature, oxygen availability, and overall water quality [11].

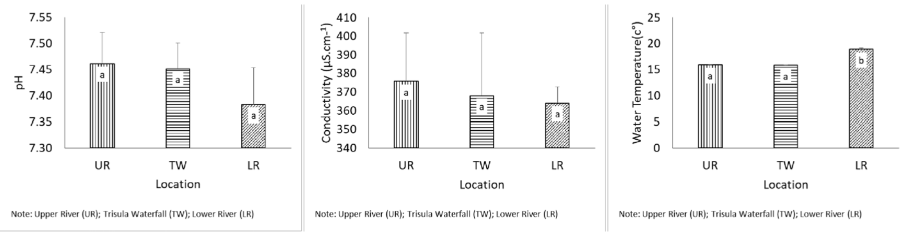
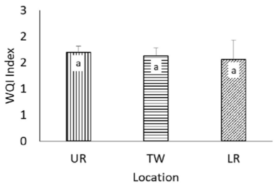


Fig. 6. Average pH, temperature, and conductivity at each station. (The same letter indicates no significant difference between areas at the $\alpha = 0.05$ level, ANOVA–Tukey HSD).

The range of conductivity readings was 364–375.67 µS cm^{-1} (Figure 6), with no discernible variations between sites. Chloride, nitrate, sulfate, phosphate, sodium, magnesium, and calcium are among the dissolved ions from both natural and man-made activities that are present in this value, which is regarded as high. It is believed that land erosion, agricultural leftovers, and household trash are the primary sources of these ions. High conductivity can disrupt aquatic organisms by increasing osmotic stress [12]. From an ecological perspective, this situation can restrict primary productivity, alter the organization of benthic macroinvertebrate groups, and lower water quality. Socially, the ecosystem's ability to deliver environmental services and visitors' comfort are both impacted by the deterioration of water clarity and quality. Therefore, waste control, riparian vegetation conservation, and sustainable tourism management are needed to maintain water quality in Trisula waterfall.

Water Quality Index (Prati)

Based on the results of the water quality evaluation using the Prati implicit index with dissolved oxygen, pH, and nitrate parameters, the pollutant value obtained in the upper river was ±1.70, Trisula waterfall ±1.63, and the lower river ±1.56 (Figure 7). Lower values indicate better water quality, so the condition of the lower river is considered the best. In general, all three locations still show water conditions suitable for daily needs and agriculture, although there is variation between locations. However, the dissolved oxygen level only meets the class two category according to Government Regulation of the Republic of Indonesia No. 82 of 2001, which means the water is suitable for water recreation, fisheries, and livestock, but does not yet meet the requirements for drinking water. Limited dissolved oxygen has implications for low primary productivity, increased oxygen competition between organisms, and reduced optimization of ecosystem services, both supporting and cultural, including tourism comfort.



Note: Upper River (UR); Trisula Waterfall (TW); Lower River (LR)

Fig. 7. Prati Implicit Index value at each observation station (the same letter indicates no significant difference between stations; ANOVA–Tukey HSD, α = 0.05).

In addition to oxygen, nitrate levels approaching the threshold of 10 mg L^{-1} also pose a risk of eutrophication if excessive accumulation occurs, especially in stagnant water ecosystems [13]. Aquatic life may be harmed by a declining pH, which denotes greater acidity. To maintain ecosystem services like clean water supplies, biodiversity support, and tourist attractions, this confluence of circumstances necessitates rigorous management. Riparian habitat management that can lower erosion and pollutant inputs must be the focus of pollution control initiatives. Environmental restoration is crucial for strengthening regulatory services, while enclave community activities need to be addressed through communication, education, and community-based conservation practices. In agriculture, more ecologically friendly and easily biodegradable natural sources of N and P should be used in place of manufactured fertilizers. Through these efforts, the natural environment of Trisula waterfall can be better conserved, ensuring healthier aquatic ecosystems and the long-term provision of ecosystem services.

Benthic Macroinvertebrates

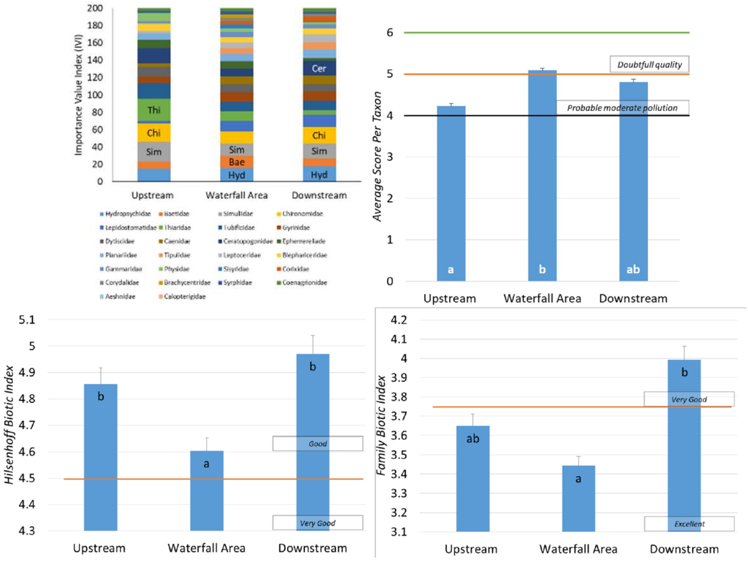


Fig. 8. Importance Value Index and ASPT, HBI, FBI at each observation station (the same letter indicates no significant difference between stations; ANOVA-Tukey HSD, α = 0.05).

Benthic macroinvertebrates were used as bioindicators to evaluate water quality and the regulating capacity of the aquatic ecosystem. A total of 25 benthic families were recorded across all stations, with higher taxonomic richness at the Trisula waterfall site compared to upstream and downstream sections (Figure 8). Community structure analysis revealed co-dominance of semi-sensitive and tolerant taxa at upstream and downstream sites, particularly Thiaridae, Chironomidae, and Simuliidae, indicating moderate environmental disturbance. In contrast, the waterfall site was characterized by a higher abundance of sensitive taxa such as Hydropsychidae and Baetidae, reflecting better ecological conditions.

Shannon-Wiener diversity indices were highest at the waterfall site, indicating greater ecosystem stability. ASPT values suggested heavy pollution at upstream and downstream sections, while the waterfall site showed light pollution levels. HBI and FBI values further confirmed low to moderate organic pollution, with the waterfall site consistently exhibiting better water quality than downstream areas. Overall, benthic macroinvertebrate indices demonstrate that the Trisula waterfall ecosystem retains a strong capacity to regulate pollutant inputs despite physicochemical pressures [14]. However, discrepancies between biological and physicochemical indicators highlight the importance of integrating both approaches for accurate water quality assessment.

4 Conclusions

Trisula Waterfall provides important ecosystem services for agriculture, domestic use, and tourism. Air discharge is relatively stable, while nitrate (6.83-7.63 mg L^{-1}) and orthophosphate (0.23-0.27 mg L^{-1}) concentrations remain within Indonesian standards, despite increasing agricultural pressure. Prati Index values (1.56-1.70) indicate generally good air quality, but dissolved oxygen limits suitability for direct consumption. Benthic macroinvertebrates exhibit stronger regulatory capacity in the waterfall area. Sustainable nutrient management, watershed restoration, and integrated monitoring are essential to maintain ecosystem services.

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