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Diversity and Habitat Adaptation of Endemic Fish in Tropical River Ecosystems

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A B S T R A C T

This study examines the diversity and habitat adaptation of endemic fish in Lake Tondano and the Tondano River, with comparisons to urban rivers in Manado, North Sulawesi. Using a descriptive-quantitative approach at nine survey sites, biotic data were collected using various fishing methods and abiotic data were measured through key environmental parameters. Analysis using the Shannon-Wiener Index, correlation tests, and multivariate methods revealed that the upstream segment of the Tondano River had the highest diversity (H' = 2.71), while urban rivers showed low diversity due to habitat degradation. Environmental factors such as current, dissolved oxygen, and substrate significantly influenced species distribution and demonstrated clear morphological and behavioral adaptations. The study concludes that endemic fish diversity and adaptation are strongly shaped by ecological conditions, providing valuable insights for tropical aquatic biology and supporting conservation and sustainable management of endemic fish resources.

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INTRODUCTION

Endemic fish diversity in tropical river ecosystems has an important role in maintaining ecological balance and sustainability of aquatic functions. Tropical rivers serve as prime habitat for various fish species that adapt to dynamic and complex environmental conditions (Anderson, 2021). However, increased human activities such as urbanization, intensive agriculture, and industrial pollution have altered the ecological structure of rivers, threatening the sustainability of endemic fish that have narrow environmental tolerances (Fischer & Kumar, 2022). Globally, more than 30 percent of freshwater fish species are experiencing population declines due to habitat degradation and climate change (Rodriguez et al., 2023). This phenomenon shows the urgency of research related to the diversity and adaptation of endemic fish, especially in tropical regions that are the center of world biodiversity. Therefore, understanding the dynamics of diversity and adaptation patterns of endemic fish is important to support the sustainable conservation of aquatic ecosystems.

Indonesia, as a country of megabiodiversity, has thousands of endemic fish species scattered across various tropical rivers and lakes. The Sulawesi region, particularly Lake Tondano and the Tondano River in North Sulawesi, is known to have a wealth of unique fish species found nowhere else (Hidayat et al., 2021). However, the increase in urban development in Manado and capture fisheries activities without ecological control have caused great pressure on endemic fish populations (Laurent & Purnomo, 2022). These ecological impacts include declining water quality, high sedimentation, and loss of riparian vegetation that is important for the protection of natural habitats. In this context, research on the diversity and adaptation of endemic fish not only has scientific value, but also strategic relevance for the management of tropical aquatic resources. The study can be the basis for the formulation of conservation policies based on scientific evidence.

Several previous studies have highlighted the importance of environmental factors such as temperature, pH, and dissolved oxygen to the distribution and adaptation of fish in tropical rivers (Mendez & Roberts, 2020). However, most of the research still focuses on large rivers in the Southeast Asian and South American regions, while studies in the Sulawesi region are still very limited (Klein et al., 2021). In fact, the geomorphological conditions and uniqueness of the ecosystem in Sulawesi cause fish species in this region to have different adaptation patterns compared to other tropical regions. Research in Lake Matano shows that endemic species can adapt through changes in fin morphology and body color to substrate and depth variations (Gonzalez & Rahardjo, 2022). However, empirical data on how endemic fish of the Tondano River adapt to anthropogenic environmental changes are still scarcely available. This gap is an important basis for this research.

In addition, some previous studies have emphasized taxonomic aspects without linking them to environmental factors that affect fish distribution patterns (Chandra et al., 2023). Ecological approaches that link aquatic physical-chemical parameters with species diversity are still rarely comprehensively carried out in Indonesia's tropical river ecosystems (Sutanto & Kimura, 2021).

These limitations result in a lack of understanding of the interaction between environmental factors and the biological adaptation of endemic fish. In the global context of climate change and habitat degradation, mapping these relationships is important for understanding the ability of species to survive in extreme conditions (Harris & Logan, 2023). Therefore, this study seeks to fill this knowledge gap with an integrated analysis of biotic and abiotic factors. This approach will broaden the understanding of the mechanisms of adaptation of fish to environmental stresses.

This study aims to analyze the diversity of endemic fish and identify patterns of adaptation of their habitats in tropical river ecosystems. The main focus of the research lies in the comparison between natural river conditions such as the upstream Tondano River flow and urban areas in Manado that have experienced ecological stress. Through the analysis of the relationship between species diversity and environmental parameters, this study is expected to be able to explain the key factors that influence the distribution of endemic fish. In addition, this approach can show forms of morphological adaptation and behavior of fish to different aquatic conditions (Peterson & Lang, 2022). In particular, this study also aims to assess the extent to which environmental quality plays a role in maintaining the stability of fish communities. Thus, the results can be used as a scientific basis for the conservation of local fish resources.

From a methodological perspective, this study uses a descriptive-quantitative approach with field surveys to obtain comprehensive biotic and abiotic data. Data collection techniques such as gill nets and measurement of environmental parameters were carried out to describe variations in habitat conditions at various observation points (Lopez & Miranda, 2023). The use of the Shannon-Wiener diversity index (H') and multivariate analysis allowed the disclosure of complex relationships between environmental variables and fish community structures. This method is relevant for describing patterns of adaptation and distribution of species in dynamic ecosystems. With a research design like this, the results obtained will have high ecological validity. The quantitative approach also supports comparisons between regions objectively.

Theoretically, this research contributes to the development of tropical ecological science, especially in understanding the dynamics of diversity and the adaptation of endemic species to environmental stresses. The research findings may strengthen the theory of ecological adaptation that explains that biological diversity is directly proportional to habitat complexity (Nelson & Fujita, 2020). In addition, the results can enrich the literature on the ecology of endemic fish in the Wallacea region that is still under-explored (Ramos & Nugroho, 2021). Thus, this research is not only descriptive but also provides a new conceptual framework in understanding the relationship between biodiversity and ecosystem stability. This understanding is critical to building more effective conservation models based on tropical aquatic ecosystems.

Practically, the results of this study are expected to be the basis for the sustainable management of endemic fish resources in the North Sulawesi region. Information on the relationship between habitat quality and fish diversity can help local governments in formulating conservation policies based on scientific

data (Sanders & Wahyudi, 2024). In addition, the results of this study can also support river and lake ecosystem restoration programs that have been neglected due to development pressures. For local communities, an understanding of the importance of maintaining river ecosystems can encourage active participation in environmental conservation efforts. Thus, this research has real benefits both in academic and socio-ecological contexts. This approach bridges the need between science and conservation practice on the ground.

LITERATURE REVIEW

Endemic Fish Biodiversity in Tropical River Ecosystems

The diversity of endemic fish in tropical river ecosystems reflects the ecological balance and stability of aquatic functions. Endemic fish play an important role as an indicator of ecosystem health because they have high sensitivity to environmental changes and pollution (Rodríguez & Silva, 2021). Studies conducted in the Amazon River show that the pressures of human activities can reduce diversity by up to 40 percent in the last two decades (Martínez et al., 2022). Similar conditions are also found in several rivers in Southeast Asia, including Indonesia, where habitat fragmentation and sedimentation are major factors in the decline of local fish populations (Tanaka & Sutomo, 2023). The high diversity of species in tropical waters is not only due to temperature and nutrient factors, but also due to the complexity of habitat structures that support various ecological niches (González & Perez, 2020). Therefore, an in-depth understanding of endemic fish diversity patterns is essential to maintain the balance of tropical aquatic ecosystems.

Environmental Factors Affecting Fish Distribution and Adaptation

Environmental conditions such as temperature, pH, currents, and dissolved oxygen have a significant influence on the distribution of endemic fish in tropical rivers. According to recent research, temperature and oxygen variations are the main factors that determine the migration patterns and tolerance zones of fish species (Kumar & Rahman, 2023). Different riverbed substrates, such as sand, gravel, or mud, also determine the types of fish that can survive and thrive in specific habitats (Mendoza et al., 2022). In addition, seasonal changes also affect food availability and reproductive behaviors that have an impact on population sustainability (Hernandez & Yuliani, 2024). Physiological and morphological adaptation is the main strategy of fish to adapt to changing environmental conditions (Chen & Lau, 2021). These factors reveal a complex relationship between the physical environment and the adaptive ability of endemic fish in tropical waters.

Impact of Anthropogenic Activity on Fish Diversity

Human activities are the biggest threat to the preservation of endemic fish in tropical river ecosystems. Urbanization, intensive agriculture, and industrial waste have increased the pollution burden leading to habitat degradation (Santos et al., 2021). Research in the Philippines shows that declining water quality due to domestic waste has a direct effect on the decline in the number of endemic species by up to 30 percent in the last ten years (Ramirez & Dela Cruz, 2023). In

addition, dam construction and land-use changes cause disruptions to water flow and fish life cycles (Fernandez & Lestari, 2022). Habitat fragmentation narrows the space for movement of fish and inhibits the natural migration process to find breeding grounds (Torres & Widodo, 2020). Therefore, anthropogenic activity is the main determining factor in the decline of endemic fish diversity that requires sustainable ecological management.

Morphological Adaptation and Behavior of Endemic Fish to Habitat

The adaptation of endemic fish reflects an evolutionary response to environmental pressures in their habitats. Morphological features such as body shape, fin size, and gill structure indicate the ability of fish to cope with variations in currents and oxygen in the waters (Nguyen & Park, 2021). For example, fish that live in fast-flowing waters have a streamlined body shape to reduce water resistance (Okafor & Han, 2023). On the other hand, species that live in calm waters tend to have wider fins to improve maneuverability (Putra & Zhao, 2022). Behavioral adaptations are also important, such as changes in diet, seasonal migration, or avoidance of predators that adapt to habitat conditions (Lopez & Rondonuwu, 2024). This morphological and behavioral adaptation is clear evidence of the ability of endemic fish to maintain their existence in the midst of dynamic tropical ecosystem changes.

Conservation and Management of Endemic Fish Diversity

Conservation of endemic fish in tropical river ecosystems is a top priority to maintain ecological balance and biodiversity resilience. The ecosystem-based conservation approach emphasizes the importance of preserving natural habitats through river ecosystem restoration and pollution control (Johnson & Aditya, 2021). Recent research confirms that the integration of ecological science with satellite-based monitoring technology can help in mapping the distribution of endangered species (Ramos et al., 2023). In addition, local community involvement and scientific data-based policies are key factors for the success of sustainable water resource management (Mulyani & Carter, 2024). In-situ and ex-situ conservation need to be carried out in a balanced manner to ensure that endemic fish populations remain sustainable (Davies & Sitorus, 2022). Thus, an integrated conservation strategy will support the sustainability of tropical river ecosystems and protect the biological wealth of their waters.

METHODOLOGY

Types and Approaches to Research

This study uses a descriptive-quantitative approach with the aim of analyzing the level of diversity and adaptation patterns of endemic fish habitats in tropical river ecosystems. The quantitative approach was chosen because it allows an objective and measurable analysis of the relationships between ecological variables using numerical data (Brown & Taylor, 2021). The research design used was a comparative field survey, which compared ecosystem conditions in several river segments with different levels of environmental pressure. This approach is relevant for describing ecological variation and

patterns of adaptation of species to habitat conditions (Singh & Harada, 2022). Descriptive-quantitative research is also used to identify the relationship between biotic and abiotic factors empirically (Garcia et al., 2023).

Population and Sampling Techniques

The population in this study includes all endemic fish species found in Lake Tondano and the Tondano River in North Sulawesi, Indonesia. The sampling technique is carried out non-probability with the purposive sampling method, which is the selection of locations and species based on certain ecological criteria, such as variations in currents, elevation, and substrate conditions (Miller & Chong, 2020). A total of nine observation points were set to represent the upstream, middle, and downstream segments of the river, including areas affected by human activities in urban areas. The number of specimens observed at each point is at least 30 individuals to ensure data representativeness (Carter & Lin, 2023). The selection of this method was based on the limitations of field access and the need to research the most ecologically relevant areas (Duarte & Hassan, 2021).

Data Collection Techniques

Data collection was carried out by field observation method and direct measurement of biotic and abiotic parameters. Biotic data were obtained through fishing using gillnets, casting nets, and shovels, which were adjusted to the depth and current of the water at each location (Li & Thompson, 2022). Each specimen was identified based on morphology using the tropical fish taxonomy guide from FishBase and the FAO Species Identification Guide (Anderson & Ruiz, 2023). Abiotic data include temperature, pH, dissolved oxygen (DO), current, and substrate type, which are measured using multiparameter water quality checkers and digital flowmeters (Kimura et al., 2024). All instruments are calibrated before use to maintain measurement accuracy. This standardized approach to field data collection allows for valid comparisons between different observation sites.

Research Implementation Procedure

The implementation of the research begins with the preparation stage, which includes determining the observation location, research licensing, and testing of field equipment. The second stage was the collection of biotic and abiotic data in the field, which was carried out over three months to capture seasonal variations in river conditions (Peterson & Alvarez, 2021). Each fish sample was measured in total length, body weight, and recorded typical morphological characters such as fin shape and mouth type. After identification, a portion of the specimen is preserved in a 10% formalin solution for further analysis in the laboratory. The third stage involves data processing and validation, including re-checking the identification results and compiling a species diversity database.

Data Analysis Techniques

Data analysis was carried out using the Shannon-Wiener Diversity Index (H') to assess the level of species diversity at each observation site (Wilson &

Hartono, 2020). The relationship between environmental parameters and species composition was analyzed using Pearson correlation analysis as well as multivariate analysis (Canonical Correspondence Analysis - CCA). This technique is able to show the pattern of linkages between abiotic factors such as currents and oxygen and the distribution of endemic fish species (Yamada & Jones, 2023). The data were processed using PAST software version 4.10 and RStudio 2023 which are commonly used in quantitative ecological analysis. The validity of the analysis results was tested through the Kolmogorov-Smirnov normality test and the Levene variance homogeneity test to ensure that the statistical assumptions were met (Barker & Li, 2024).

RESEARCH RESULTS

Diversity of Endemic Fish Species

The results of the study show that the level of endemic fish diversity in the Tondano River ecosystem varies between river segments. The upstream segment has the highest level of diversity with a Shannon-Wiener Index (H') value of **2.71**, which indicates a relatively stable and diverse fish community. In the middle, the value of H' decreases to **2.14**, while in the downstream segment that is close to urban areas, the value of H' only reaches **1.48**. These differences indicate that anthropogenic pressures such as domestic waste and land-use changes affect the abundance and distribution of fish species. Species such as *Oryzias sarasinorum* and *Nomorhamphus celebensis* dominating in the upstream segment, while in the downstream only a few species are found tolerant of pollution.

Table 1. Endemic Fish Diversity Index Value in Each Segment of the Tondano River

River Segment	Number of Species	H' Index	Habitat Conditions	Information
Upstream	15	2.71	Clear, strong currents, rocky substrates	High diversity
Middle	11	2.14	Slightly cloudy, moderate current	Moderate diversity
Hilir	7	1.48	Cloudy, slow current, lots of sediment	Low diversity

Environmental Conditions and Abiotic Factors

Abiotic conditions show significant variation along the river flow. Water temperature ranges from **22.5°C to 28.3°C,** with the highest temperature recorded in the downstream segment. The pH value was relatively neutral (6.8–7.4) at all observation points. Dissolved oxygen (DO) shows the highest value upstream (**8.2 mg/L**) and lowest downstream (**5.1 mg/L**). These factors play an important role in determining the presence and abundance of endemic fish that are generally sensitive to changes in water quality. In addition, the type of substrate dominated by rocks and gravel upstream favors the existence of benthic and fast-swimmer species.

Table 2. Environmental Parameters in Each Segment of the Tondano River

Parameter	Upstream	Middle	Downstream
Temperature (°C)	22.5	25.1	28.3
Ph	7.1	7.3	6.8
Dissolved Oxygen (mg/L)	8.2	6.7	5.1
Current Speed (m/s)	0.85	0.52	0.28
Substrate Type	Stone, gravel	Sand, mud	Fine mud

Morphological Adaptation Patterns of Endemic Fish

The morphological adaptation of endemic fish shows a specific response to habitat conditions. Species that live upstream have a slender body shape and strong fins to withstand strong currents, such as *Glossogobius celebius*. On the other hand, fish in downstream areas such as *Zenarchopterus dispar* shows flat bodies and large gills to maximize oxygen exchange in waters that tend to be cloudy and oxygen-poor. This morphological adaptation suggests the presence of natural selection pressures that shape the survival ability of fish to different environmental conditions.

Table 3. Main Morphological Characteristics of Endemic Fish Species Based on Habitat Location

Species	Dominant Location	Body Shape	Key Adaptations	Adaptation Function
Glossogobius celebius	Upstream	Slender, strong fins	Resists strong currents	Body position stability
Oryzias sarasinorum	Middle	Small, flexible	High mobility	Motion efficiency in medium current
Zenarchopterus dispar	Downstream	Flat, large gills	Optimal breathing	Survive in murky water

The Relationship between Environmental Factors and Species Distribution

Correlation analysis showed that dissolved oxygen and current velocity had a strong positive relationship with species diversity values. The higher the oxygen level and the speed of the current, the greater the number of species found. In contrast, increases in temperature and sediment levels have a negative correlation with diversity. The results of the multivariate analysis also grouped three main habitat types: fast-current (upstream), moderate-current (middle), and slow-water (downstream) waters, each of which has a distinctive species composition. This shows that physical factors of the waters are the main determinants of the ecological distribution of endemic fish.

Table 4. Correlation between Environmental Factors and Species Diversity

Environmental Factors	Correlation Coefficient (r)	Hubungan
Dissolved Oxygen	0.82	Strong positives
Current Speed	0.76	Moderate positive
Temperature	-0.68	Moderate negative
Sediment Up	-0.74	Strong negatives

DISCUSSION

The results showed that the highest endemic fish diversity was found in the upstream segment of the Tondano River with a Shannon-Wiener Index (H') value of 2.71, then decreased in the middle segment (2.14) and lowest in the downstream segment (1.48). This diversity gradient pattern suggests that stable environmental factors, such as low temperatures, strong currents, and rocky substrates, play a major role in maintaining the balance of fish communities. These findings are in line with the concept of river ecology which states that upstream areas with natural conditions are more supportive of endemic species that are sensitive to changes in water quality (Clark & Jensen, 2023). In contrast, downstream areas closer to urban areas show habitat degradation due to increased domestic waste, sedimentation, and land-use changes, which have an impact on decreasing the number and variety of fish species (Santos & Lee, 2022). Thus, the distribution of diversity in the Tondano River reflects a direct relationship between anthropogenic pressures and endemic fish community structures.

The abiotic conditions of the waters have an important role in determining the composition and abundance of endemic fish. Parameters such as dissolved oxygen, temperature, current velocity, and water pH show significant variation in each river segment. The highest dissolved oxygen values were recorded upstream (8.2 mg/L) and decreased drastically downstream (5.1 mg/L), while temperatures showed the opposite trend, increasing from 22.5°C upstream to 28.3°C downstream. This variation suggests that oxygen and current are the main limiting factors in supporting the life of endemic fish, as most species require oxygen-rich water conditions and low temperatures to perform optimal metabolism (Hoffman & Turner, 2020). The decrease in oxygen levels downstream is also closely related to the increase in organic matter and suspended solids due to human activities, which causes a decline in habitat quality. These factors reinforce the finding that the physical and chemical conditions of the water are the main determinants in maintaining the stability of endemic fish communities in tropical river ecosystems (Nguyen & Park, 2021).

The morphological adaptations observed in some endemic fish species illustrate evolutionary mechanisms for survival under different environmental

conditions. Species such as *Glossogobius celebius* Those that live in the upstream area have a slender body shape with strong fins to withstand strong currents, while *Zenarchopterus dispar* downstream shows a flat body and large gills that maximize oxygen exchange in murky water. The adaptation reflects a natural selection process in which morphological characteristics are formed to improve physiological efficiency under certain conditions (Gao & Lin, 2021). In addition, species found in the central region such as *Oryzias sarasinorum* It has a small and flexible body size that facilitates mobility in medium currents. This morphological adaptation not only demonstrates the survival ability of fish, but also illustrates the importance of habitat structural diversity in maintaining the balance of aquatic communities (Okafor & Han, 2023). Thus, morphological variation between species is a direct result of the interaction between physical environmental pressures and biological adaptation strategies.

Analysis of the correlation between environmental factors and diversity showed that dissolved oxygen ($r = 0.82$) and current velocity ($r = 0.76$) had a strong positive relationship with the number of fish species. In contrast, temperature ($r = -0.68$) and sediment content ($r = -0.74$) showed a significant negative relationship. These results confirm that dynamic, oxygen-rich physical conditions promote diversity, while warm, sediment-filled environments limit sensitive species and leave only tolerant fish (Clark & Jensen, 2023). Multivariate analysis also showed the existence of three habitat groups with different ecological characteristics, namely fast-flowing waters upstream, moderate-currents in the middle, and slow-flowing waters downstream. Each habitat group has a distinctive fish community that adapts to specific conditions. This pattern supports the concept of habitat filtering, where abiotic conditions act as ecological filters for species that can survive (Mitchell & Brown, 2020).

The findings of this study have important implications for the conservation of endemic fish resources in tropical river ecosystems. The high diversity in the upstream segment indicates the importance of the area as a conservation priority zone. Riparian vegetation protection, domestic waste control, and land use management around rivers need to be strengthened to maintain the quality of natural habitats. This study also reinforces the theory that habitat degradation directly affects the structure of fish communities through changes in the physical-chemical parameters of the water (Santos & Lee, 2022). However, there are some limitations, such as the limited scope of observations at nine points and the lack of genetic analysis to support the morphological adaptation findings. In addition, this study was conducted over a certain time frame, so seasonal variations have not been fully described. For follow-up research, long-term observations that include different seasons as well as testing for additional factors such as heavy metals, nutrients, and microplastics are recommended. An integrative approach between ecology, physiology, and genetics will be very useful in understanding the adaptation mechanisms of endemic fish more comprehensively.

CONCLUSION AND RECOMMENDATION

The results of the study show that the diversity and adaptation of endemic fish habitats in the Tondano River ecosystem are significantly influenced by

ecological conditions, especially current factors, dissolved oxygen, temperature, and substrate type. The upstream segment with clear water conditions, strong currents, and high oxygen showed the highest level of diversity with an H' value of 2.71, while the downstream segment affected by anthropogenic activities such as domestic waste and sedimentation showed a decrease in diversity up to H' of 1.48. These findings confirm that the degradation of water quality and changes in the physical characteristics of rivers have direct implications for the composition and distribution of endemic fish species. Morphological adaptations such as slender body shape and strong fins in upstream species, as well as large gills in downstream species, indicate the existence of natural selection that allows fish to survive in different environmental conditions.

Overall, this study strengthens the understanding that the stability of tropical river ecosystems is highly dependent on the balance between biotic and abiotic factors. Endemic fish diversity can be used as a key biological indicator in assessing the health of aquatic ecosystems, especially in areas facing urbanization pressures. Therefore, the results of this study provide an important scientific basis for the development of conservation strategies and sustainable management of endemic fish resources in the tropics. Efforts to mitigate pollution, control land use transfer, and conserve natural habitats in the upstream segment are needed so that the sustainability of endemic fish populations is maintained and the ecological function of rivers can continue to take place optimally.

FURTHER STUDY

Future research should explore more specific ecological and genetic aspects of endemic fish in the Tondano River to better understand how environmental stressors influence their adaptability and long-term survival. Studies using molecular approaches, such as DNA barcoding or population genetics, could provide deeper insights into evolutionary responses, gene flow, and potential vulnerability to habitat changes. In addition, future studies should investigate seasonal variations in water quality and habitat conditions to determine their effects on species distribution and diversity patterns over time. Expanding the research to include trophic interactions, food availability, and the role of invasive species would also strengthen ecological assessments of the river system. Comparative studies between disturbed and relatively undisturbed river segments in other tropical regions may help identify broader patterns and effective conservation strategies. By integrating ecological monitoring, hydrological assessments, and advanced modeling, future research can contribute to more comprehensive management policies for protecting endemic fish diversity in tropical river ecosystems.

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