EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

*Ecological Engineering & Environmental Technology*, 25(12), 290–304
https://doi.org/10.12912/27197050/194815
ISSN 2719–7050, License CC-BY 4.0

Received: 2024.10.03
Accepted: 2024.10.23
Published: 2024.11.01

# Multipurpose Riparian Zone Design – Enhancing Conservation and Pollution Control for a Sustainable Lake Tondano

Arrijani[1*], Tineke Makahinda[2], Kurniahtunnisa[3], Mellyatul Aini[3], Aufa Maulida Fitrianingrum[4], Tika Putri Agustina[5]

[1] Department of Biology, Universitas Negeri Manado, Unima Campus Street, Tonsaru, South Tondano District, Minahasa, Indonesia

[2] Department of Physics Education, Universitas Negeri Manado, Unima Campus Street, Tonsaru, South Tondano District, Minahasa, Indonesia

[3] Department of Science Education, Universitas Negeri Manado, Unima Campus Street, Tonsaru, South Tondano District, Minahasa, Indonesia

[4] Department of Physics, Universitas Negeri Manado, Unima Campus Street, Tonsaru, South Tondano District, Minahasa, Indonesia

[5] Department of Biology Education, Universitas Negeri Manado, Unima Campus Street, Tonsaru, South Tondano District, Minahasa, Indonesia

* Corresponding author's e-mail: arrijani@unima.ac.id

## ABSTRACT

This research focuses on developing a multipurpose riparian zone designed to effectively reduce erosion and control nutrient flow into Lake Tondano. The goal is to enhance both conservation and pollution control strategies for sustainable ecosystem management. Conducted at Lake Tondano in Minahasa, Indonesia, the research followed three main stages: data collection, analysis, and design. The data collection included a vegetation survey of riparian species, land use mapping, and measuring nitrogen and phosphorus levels in lake sediments. A total of 91 plant species from 60 genera and 42 families were documented. Based on their Importance Value Index (IVI), non-invasive status, and nutrient absorption capabilities, 15 species were selected for restoration in areas with high nutrient concentrations, with sediment levels recorded at 0.09% nitrogen and 0.06% phosphorus in impacted zones. These plant species were carefully identified and rigorously tested, originating from intact riparian zones. They will be strategically employed in areas facing significant challenges from nutrient overloading. Using QGIS analysis, a riparian zone measuring 100 × 30 m was designed at coordinates 1.1745604 latitude and 124.8972748 longitude, targeting areas most impacted by nutrient pollution, which poses a risk of eutrophication and negatively affects aquatic ecosystems. The multipurpose riparian zone incorporates distinct wet, transition, and dry zones, employing a zigzag planting pattern to optimize pollutant filtration and nutrient uptake. This design effectively addresses critical issues of erosion and nutrient excessive enrichment, promoting ecological health and biodiversity in the region. The novel contributions of this study include identifying specific plant species capable of thriving in nutrient-rich sediments and quantifying their nutrient absorption capacities, thereby providing a scientifically grounded model for similar conservation efforts in vulnerable ecosystems and enhancing overall resilience. However, long-term impacts on water quality require further research to assess nutrient mitigation efficacy.

**Keywords:** ecosystem restoration, lake, nutrient management, pollutant, QGIS, riparian zone.

## INTRODUCTION

Lake Tondano is the largest natural lake in North Sulawesi, covering an area of 4.638 hectares, and serves as an important ecosystem for the surrounding communities. As one of 15 prioritized lake ecosystems for conservation by the Indonesian government, this lake is vital for various activities, including agriculture, fisheries, and the provision of clean water for nearby areas.

Lake Tondano is a primary economic source for the local population. Many community members depend on the lake's ecosystem for agricultural, plantation, livestock, energy, and fisheries need, particularly the capture of Nike fish. Lake Tondano is also a source of drinking water for the cities of Manado, Minahasa, and North Minahasa. Furthermore, Lake Tondano serves as a source of electricity (hydropower). The major cities in the eastern part of North Sulawesi Province receive their electricity supply from these hydropower plants (Sittadewi, 2008). However, the management of Lake Tondano has not effectively implemented conservation principles, thus threatening the existence of its ecosystem.

Due to this, Lake Tondano is currently facing serious threats, such as pollution, sedimentation, ecosystem degradation, and overfishing. Domestic waste, agricultural runoff, fishing waste, and garbage have accumulated within the Lake Tondano ecosystem, reducing the lake's carrying capacity (Runtuwene et al., 2023). Lake Tondano has 35 inlet rivers and only one outlet river, the Tondano River, and the numerous inlets contribute to an increase in nutrients, organic materials, and pesticide residues entering the lake (Kumurur, 2002; Sittadewi, 2008). The protected area of Lake Tondano has been transformed into settlements and rice fields, even extending into the lake's waters (Karouw and Soeryanto, 2024).

Lake Tondano's ecosystem is severely threatened by water pollution and high erosion rates, which contribute to to sedimentation (Walangitan et al., 2024). During the period from 2008 to 2020, Lake Tondano also experienced high erosion rates due to changes in land cover in its catchment area, with the highest erosion rate occurring in 2017 at 7,565.7835 tons/ha/year (Raco et al., 2022). Fertilizer use in rice fields causes nitrate and ammonia levels to fluctuate annually (Wantasen and Luntungan, 2016). This pollution is worsened by the degradation of riparian and buffer zones, which once protected the lake. Since the 1950s, clove plantations have replaced riparian vegetation, contributing to increased erosion and nutrient flow into the lake. Moreover, eutrophication in Lake Tondano results from elevated nutrient levels, particularly phosphorus and nitrogen, leading to excessive algal growth that harms the aquatic ecosystem and contributes to sedimentation (Li et al., 2022). Key factors accelerating this process include poor waste management and inadequate land practices. Therefore, effective control and rehabilitation efforts are essential to restore water quality and preserve the lake's ecosystem.

Ecosystem restoration approaches are recognized globally as key components in lake conservation programs. A review of over 330 studies highlights the effectiveness of various restoration techniques, such as riparian zone rehabilitation, sediment reduction, dam removal, and floodplain restoration, which have shown positive impacts on freshwater fisheries (Coates, 2023). In critical source areas, establishing ecological riparian zones is essential for preventing downstream pollutant flow, safeguarding water quality, and promoting healthier aquatic ecosystems (Chang et al., 2021). Riparian zones, known for their high biodiversity, play a crucial role in water filtration. Their restoration not only enhances biodiversity but also reduces surface runoff, purifies groundwater, controls erosion along riverbanks and lakeshores, and filters pollutants (Bahn and An, 2020). Many studies have been conducted regarding on the issues surrounding Lake Tondano, including changes in lake area coverage, sedimentation management, and morphometric analysis. However, two main areas remain under-researched: (1) An adequate assessment of historical conditions, disrupted ecosystem processes, and limiting factors affecting biotic production in Lake Tondano; (2) Previous studies have primarily focused on identifying causes of problems without systematically designed solutions. Therefore, solution-oriented research that can aid in conserving the existence of Lake Tondano is necessary.

This research aims to develop an effective multipurpose riparian zone that reduces erosion rates and controls nutrient flow into Lake Tondano. To achieve this goal, an ecosystem restoration approach will be utilized, involving an in-depth analysis of the issues within the Lake Tondano ecosystem and the holistic application of conservation principles. This includes identifying erosion issues, nutrient flow, and declines in biodiversity in the riparian areas of Lake Tondano, as well as employing biological technologies such as phytoremediation to restore ecosystem balance and mitigate the impacts of human activities. Through this approach, integrated management strategies will be developed to design an optimal multipurpose riparian zone that maintains the sustainability of Lake Tondano.

## METHODS

The research was conducted at Lake Tondano, Minahasa, Indonesia. The research method consisted of three main stages: data collection, data analysis, and design. The data collection phase included a vegetation survey and selection of plants, land use mapping, and the measurement of nitrogen and phosphorus levels in the lake's sediments. The analysis stage involved integrating the collected data using QGIS version 3.38 software. Finally, the design stage focused on developing a multipurpose riparian zone design to address the environmental challenges faced by Lake Tondano. The research flow diagram is presented in Figure 1.

### Vegetation survey and selection of plants

The research began with a vegetation survey, followed by the selection of plants to purify water from key pollutants like nitrogen (N) and phosphorus (P). The survey, conducted between July and August 2024, assessed the diversity of riparian vegetation around Lake Tondano. Purposive sampling was used to select 10 locations, covering both disturbed and undisturbed areas to capture the environmental conditions within the riparian zone. Vegetation sampling employed the belt transect method with 1x1 meter quadrats, positioned perpendicularly from the dry zone to the wet zone near the lake and horizontally along the shoreline. This allowed for comprehensive sampling across varying moisture levels and water interactions. Non-tree species collected were prepared as herbarium specimens for taxonomic identification at Yayasan Generasi Biologi Indonesia.

Following the survey, 15 plant species were selected based on their Importance Value Index (IVI), their status as non-invasive species, and their potential to purify water by absorbing nitrogen and phosphorus. The selection criteria emphasized their ability to serve as bio-accumulators for phytoremediation and their capacity to act as erosion barriers. A combination of trees, shrubs, and grasses was chosen to form the basis of the riparian zone model, aimed at enhancing water quality and ecosystem health around Lake Tondano. These species were then tested for their ability to absorb nitrogen and phosphorus, with laboratory analysis conducted at the Manado Center for Industrial Standardization and Service. As a result, the 15 identified and tested plant species from the intact riparian zone will be utilized for restoration in areas with elevated nitrogen and phosphorus levels, as determined by our analyses.

### Land use mapping

Land use mapping around Lake Tondano is based on data from Sulawesi River Regional

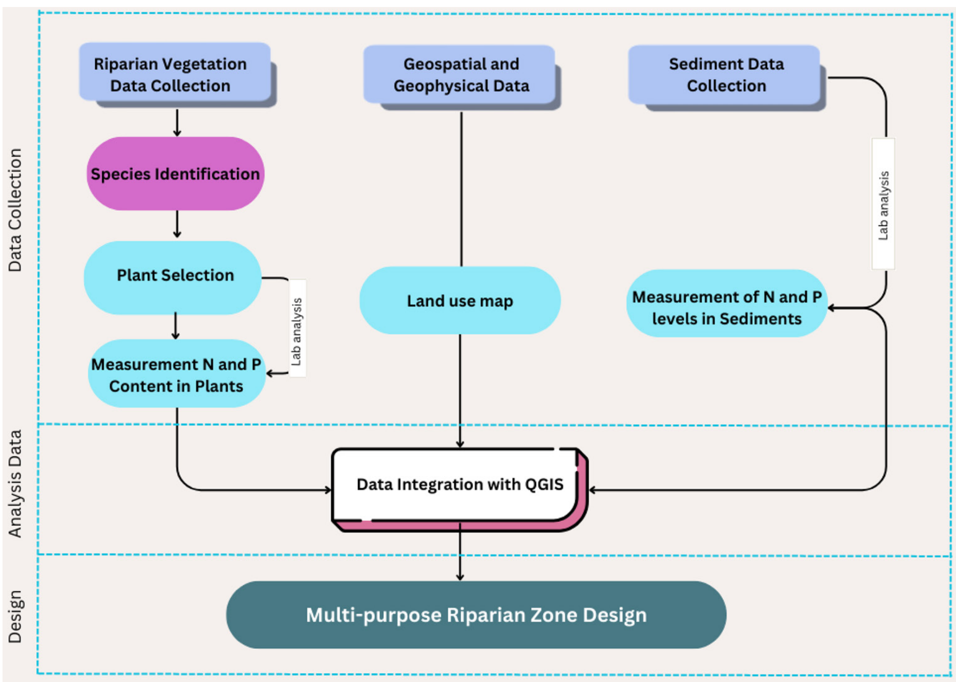


**Figure 1**. Research flow diagram

Center 1 (BWS), which manages regional land and environmental resources. This mapping categorizes various land uses, such as agriculture, residential areas, and natural habitats, allowing researchers to identify patterns that may contribute to environmental challenges like erosion and nutrient pollution. The land use map obtained from this process is utilized to design the riparian zone using QGIS software, highlighting potential areas for restoring vegetation and converting unused or abandoned land into effective filtering zones.

### Measurement of N and P levels in Lake Tondano sediments

The measurement of Nitrogen (N) and Phosphorus (P) levels in the sediments of Lake Tondano was conducted to understand nutrient distribution, which serves as an indicator of pollution levels and a basis for determining the riparian zone. Sediment samples were taken from seven strategic points in the lake, chosen based on hydrological maps and runoff from settlements, agricultural land, and river flows. Sampling was performed using a Van Veen Grab, and each sampling point was documented using GPS to ensure location accuracy. The obtained sediment samples were then stored in labeled sterile containers and kept in cold conditions to maintain their stability until they reached the laboratory.

In the laboratory, the Nitrogen content was analyzed using the Kjeldahl method, which involves digesting with concentrated sulfuric acid and titrating to calculate the concentration of N. Meanwhile, the Phosphorus content was measured through spectrophotometry after extracting the phosphate with strong acid. The results of the N and P analyses were processed using QGIS software to generate nutrient distribution maps across the lake. These maps revealed variations in N and P concentrations at different locations, helping to identify areas with the highest levels of pollution that require restoration actions.

### Multipurpose riparian zone design

The final step of this research is to develop an optimal riparian zone model that aligns with local ecosystem conditions. This model covers a plot of land 100 meters wide parallel to the lake and 30 meters perpendicular, starting from the flood zone and including wet, semi-dry, and dry zones. The dry zone has a width of about 10 meters, with adjustments based on local conditions and land ownership. geographic information systems (GIS) using QGIS version 3.38 software were employed to analyze land availability for planting riparian vegetation, based on the land use map obtained from Sulawesi River Regional Center 1 (BWS). This analysis involved mapping unused or abandoned land that could function as effective filtering zones, aimed at reducing erosion and mitigating water pollution from agricultural and residential waste. This approach is expected to enhance the ecosystem quality of Lake Tondano, considering environmental variations and local needs. After selecting the appropriate plant species, the next step is determining the required amount of riparian vegetation for successful restoration.

The riparian buffer zone is implemented in an area of 3000 m². To determine the required bioremediation ratio, a formula is used to calculate the total nitrogen and phosphorus uptake. The total nitrogen and phosphorus uptake is calculated using the following formula:

$$\text{Total nitrogen uptake} = \sum_{i=1}^{n}\left(Absorpsi\ nitrogen_{\ plant\ i} \times \frac{IVI_{plant\ i}}{\sum_{i=1}^{n} IVI_{plant\ i}}\right) \quad (1)$$

$$\text{Total phosphorus uptake} = \sum_{i=1}^{n}\left(Absorpsi\ fosfor_{\ plant\ i} \times \frac{IVI_{plant\ i}}{\sum_{i=1}^{n} IVI_{plant\ i}}\right) \quad (2)$$

After that, the limiting factor is determined based on the comparison between nitrogen and phosphorus. If the ratio of nitrogen to total nitrogen uptake is greater than the ratio of phosphorus to total phosphorus uptake, then nitrogen is considered the limiting factor. Conversely, if this is not the case, phosphorus is the limiting factor. Next, the minimum number of plants needed is determined based on the identified limiting factor. If nitrogen is the limiting factor, the formula to calculate the minimum number of plants is:

$$Minimum\ number\ of\ plants = \frac{Nitrogen \times N_{ratio_i}}{Total\ nitrogen\ uptake \times Absorpsi\ nitrogen_{plant_i}} \quad (3)$$

If phosphorus is the limiting factor:

$$Minimum\ number\ of\ plants = \frac{Fosfor \times P_{ratio_i}}{Total\ phosphorus\ Uptake \times Absorpsi\ fosfor_{plant_i}} \quad (4)$$

To simplify the calculations, the authors have created an application that computes the bioremediation ratio based on the formulas provided above. This application is accessible at https://plantbioremediationcalculator.arsakara.com/.

## RESULTS AND DISCUSSION

### Vegetation survey and selection of plants

Field observations around Lake Tondano revealed a rich diversity of plant species that contribute to the riparian ecosystem. The vegetation survey identified 91 plant species from 60 genera and 42 families, with most being angiosperms, or flowering plants, which dominate the riparian zone. The analysis of these plant communities was based on the Importance Value Index (IVI), a measure that combines relative density, frequency, and dominance. Key species identified with high IVI values include *Leersia hexandra* Swartz, *Ischaemum latifolium* (Sprengel) Kunth, *Phragmites australis* (Cav.) Trin. ex Steud., *Colocasia esculenta* (L.) Schott, *Cyperus platystylis* R.Br., *Ipomoea aquatica* Forssk., *Dinebra chinensis* (L.) P.M. Peterson and N. Snow, *Urochloa mutica* (Forssk.) T.Q. Nguyen, *Ludwigia octovalvis* (Jacq.) P.H. Raven, and *Commelina* sp. These species not only dominate the riparian zone due to their abundance and distribution, but they also play a significant role in shaping the structure and function of the ecosystem. Their dominance, as indicated by their high Importance Value Index (IVI) values, reflects their adaptability and ecological importance in maintaining the health and stability of the riparian environment.

Among these, *Leersia hexandra* Sw. and *Ischaemum latifolium* (Spreng.) Kunth are the two most dominant species in the buffer zone of Lake Tondano, thriving in both flooded and dry areas. Their presence plays a crucial role in erosion control and maintaining soil stability along the lake's edge. *Leersia hexandra* is known for its resilience in various environmental conditions, ranging from dry to wet and humid areas. Several studies highlight this plant's ability to absorb heavy metals through its roots, making it beneficial for phytoremediation in wetlands contaminated with heavy metals such as Cr(III) and Cu(II) (Chen et al., 2022). Furthermore, the presence of endophytic bacteria in the roots of *L. hexandra* can reduce heavy metal toxicity by converting Cr(VI) into the less harmful Cr(III) form (Lin et al., 2019; Liu et al., 2014).

*Phragmites australis*, a perennial grass from the Poaceae family, is also a dominant species in the riparian zone of Lake Tondano, particularly in drier areas with muddy soil conditions. This plant has long been utilized by humans for various purposes, including water purification by enhancing bacterial activity at the roots through oxygen provision via its aerenchyma system. Therefore, the dominance of *Phragmites australis* in the riparian zone holds significant potential for improving water quality in Lake Tondano (Ailstock et al., 2001).

Additionally, *Colocasia esculenta*, which often grows alongside *Leersia hexandra* and *Ischaemum latifolium*, has been shown to significantly reduce water pollutants such as suspended solids, $BOD_5$, COD, nitrate, and phosphate. *C. esculenta* has proven to be more effective in wastewater treatment compared to other plant species (Balachandran et al., 2018). Moreover, research indicates that subsurface flow systems (SSF) using *Colocasia esculenta* as a primary component can effectively reduce nutrient levels such as nitrate and phosphate, as well as organic matter in wastewater. This occurs because *C. esculenta* can absorb these nutrients through its roots, thus decreasing excess nutrient concentrations that can lead to significant eutrophication or water quality decline (Bindu et al., 2008).

The aquatic vegetation in this area is primarily dominated by *Eichhornia crassipes* (Mart.) Solms and *Ipomoea aquatica* Forssk., which thrive abundantly due to their rapid growth rates and high nutrient availability in the lake caused by sedimentation and soil erosion, a condition known as eutrophication. The eutrophication in Lake Tondano is exacerbated by human activities such as deforestation and waste disposal, which increase nutrient levels and lead to outbreaks of aquatic plants (Qin et al., 2013; Setyono and Himawan, 2018).

Out of the 91 identified plant species, selections were made based on their high IVI (Importance Value Index), invasiveness traits verified through various websites (such as the Global Invasive Species Database and other invasive plant databases), and their root capabilities in controlling erosion, as supported by literature studies. The selection of these fifteen species also considered their diverse life forms, including trees, shrubs, and grasses. This diversity is essential, as each type of plant plays a unique role in enhancing ecosystem resilience and functionality (Dunn et al., 2022). Trees provide shade and habitat, shrubs contribute structural diversity and support wildlife, while grasses stabilize soil and improve water infiltration. Together, these varied life forms create a robust riparian zone capable of effectively addressing nutrient pollution and promoting ecological health.

This process led to the identification of 15 riparian plant species from intact riparian zones, which will be utilized in the design of a multipurpose riparian zone aimed at restoring areas with elevated nitrogen and phosphorus levels, as determined by our analyses. These plants were further analyzed for their ability to absorb nitrogen and phosphorus from the environment. The measurements of nitrogen and phosphorus absorption were conducted with two repetitions. The testing was carried out with samples taken from locations both far from and close to human activities. Certain plant species, such as *Vigna luteola*, were not found in areas far from human activities, while *Metroxylon sagu* was found near human activities, although it was difficult to collect due to high-water conditions. The results of the nitrogen (N) and phosphorus (P) content analysis for the plant species are presented in Table 1.

The analysis of nitrogen (N) and phosphorus (P) absorption capacities among 15 riparian vegetation species revealed significant variability in their potential for nutrient management within the ecosystem. For instance, *Phragmites australis* exhibited the highest average total nitrogen absorption at 1.12% and phosphorus absorption at 0.50%, highlighting its effectiveness in nutrient uptake. This finding is consistent with previous research emphasizing the role of *Phragmites australis* in wetland environments, where it contributes to nutrient cycling and water quality improvement (Ailstock et al., 2001). In contrast, *Vigna luteola* demonstrated minimal absorption, particularly in areas further from human activities, suggesting a more limited ecological role.

Species like *Leersia hexandra* and *Ischaemum latifolium*, which thrive in diverse environmental conditions and show substantial nitrogen absorption (0.69% and 0.38%, respectively), could be leveraged for bioremediation efforts to mitigate nutrient pollution (Chen et al., 2022). The data also indicated that proximity to human activity influenced the presence of certain plant species. For instance, *Metroxylon sagu* was primarily found near human activities, although it was difficult to sample due to high water conditions, illustrating the impact of anthropogenic factors on plant distribution and ecosystem health (Qin et al., 2013).

These findings underscore the crucial role of selecting the most appropriate plant species for the design of a multipurpose riparian zone. Among the species surveyed, fifteen were identified for their high importance value index (IVI) and strong ability to absorb excess nutrients, particularly nitrogen and phosphorus. These plants, sourced from well-preserved riparian zones, have been carefully chosen for their ecological benefits and will be used in restoring and conserving areas with elevated nutrient levels. By using these

**Table 1.** The results of N and P content analysis on the plant species

| No. | Spesies | Sample 1 | | Sample 2 | | Average total nitrogen | Average total phosporus (P) |
|---|---|---|---|---|---|---|---|
| | | Content | | Content | | | |
| | | N (%) | P (%) | N (%) | P (%) | | |
| 1 | *Cyperus platystylis* | 0.46 | 0.51 | 0.41 | 0.30 | 0.43 | 0.40 |
| 2 | *Leersia hexandra* Sw. | 0.77 | 0.57 | 0.61 | 0.60 | 0.69 | 0.58 |
| 3 | *Urochloa mutica* (Forssk.) T.Q.Nguyen | 0.21 | 1.27 | 0.12 | 0.40 | 0.16 | 0.83 |
| 4 | *Vigna luteola* | - | - | 0.09 | 0.32 | 0.09 | 0.32 |
| 5 | *Ischaemum latifolium* (Spreng.) Kunth | 0.66 | 0.42 | 0.10 | 0.39 | 0.38 | 0.40 |
| 6 | *Colocasia esculenta* | 0.33 | 0.33 | 0.15 | 0.31 | 0.24 | 0.32 |
| 7 | *Ipomoea aquatica* | 0.56 | 0.20 | 0.31 | 0.41 | 0.43 | 0.30 |
| 8 | *Dinebra chinensis* (L.) | 0.48 | 0.26 | 0.74 | 0.55 | 0.61 | 0.40 |
| 9 | *Phragmites australis* (Cav.) Trin. ex Steud. | 1.17 | 0.45 | 1.08 | 0.55 | 1.12 | 0.50 |
| 10 | *Diplazium esculentum* (Retz.) Sw. | 0.69 | 1.75 | 0.94 | 0.75 | 0.81 | 1.25 |
| 11 | *Ficus septica* | 0.74 | 0.58 | 0.53 | 0.63 | 0.63 | 0.60 |
| 12 | *Ludwigia octovalvis* | 0.80 | 0.32 | 0.71 | 0.56 | 0.75 | 0.44 |
| 13 | *Metroxylon sagu* | 0.86 | 0.36 | - | - | 0.86 | 0.36 |
| 14 | *Cyperus papyrus* | 1.66 | 0.65 | 0.56 | 0.37 | 1.11 | 0.51 |
| 15 | *Acrosticum aureum* L. | 0.78 | 0.33 | 0.56 | 0.99 | 0.67 | 0.66 |

species, the riparian zone design will effectively address nutrient pollution, improve water quality, and enhance ecosystem stability. This selection ensures that the riparian environment can recover and thrive, contributing to the long-term health and resilience of both the water body and the surrounding land. Future research should focus on assessing the long-term impacts of these species on water quality and their contributions to mitigating nutrient pollution, thereby enhancing the overall health of riparian ecosystems.

### Analysis of nitrogen and phosphorus distribution in Lake Tondano

To determine the appropriate amount of bioremediators and select trial locations, a crucial first step is to analyze the sediment content in Lake Tondano. This analysis aims to assess the distribution of nitrogen (N) and phosphorus (P) contamination in the lake, providing a foundation for devising an effective remediation strategy. The results from this analysis offer insight into the distribution of pollutants across various areas of the lake. The results of the N and P content analysis in Lake Tondano sediments are presented in Table 2.

Based on the collected data, the distribution of nitrogen and phosphorus across the entire Lake Tondano area was mapped using the QGIS application. This mapping aims to provide a clear visualization of pollution distribution in the lake, enabling the identification of the most affected areas. The mapping of nitrogen distribution is presented in Figure 2, and the mapping of phosphorus distribution is presented in Figure 3.

The results of the nitrogen (N) and phosphorus (P) analysis of the sediments in Lake Tondano reveal significant variations that underscore the influence of human activities in the surrounding

**Table 2.** Results of N and P content analysis in Lake Tondano sediments

| No. | Parameter | Unit | Results | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | T1 | T2 | T3 | T4 | T5 | T6 | T7 |
| | Longitude | | 124.9134528 | 124.9167839 | 124.8972748 | 124.8684067 | 124.9019788 | 124.9165992 | 124.8620934 |
| | Latitute | | 1.2842769 | 1.2308649 | 1.1745604 | 1.2319336 | 1.2697458 | 1.2826532 | 1.2152902 |
| 1. | Nitrogen (N) | % | 0.10 | 0.05 | 0.09 | 0.08 | 0.14 | 0.16 | 0.15 |
| 2. | Phosphorus (P) | % | 0.02 | 0.01 | 0.06 | 0.03 | 0.04 | 0.04 | 0.03 |

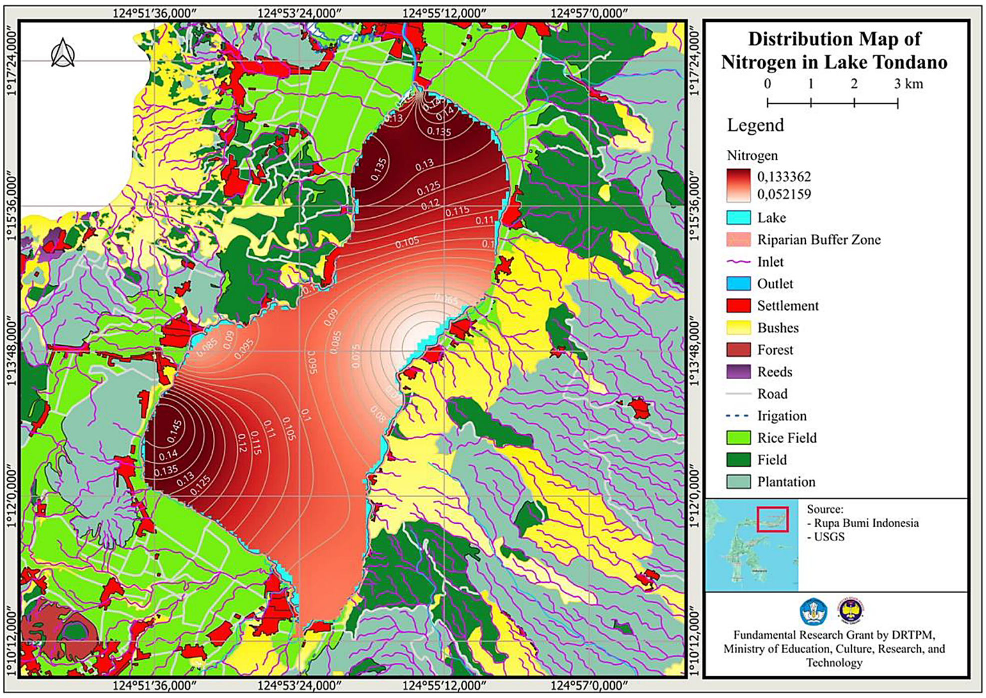


**Figure 2.** Nitrogen distribution

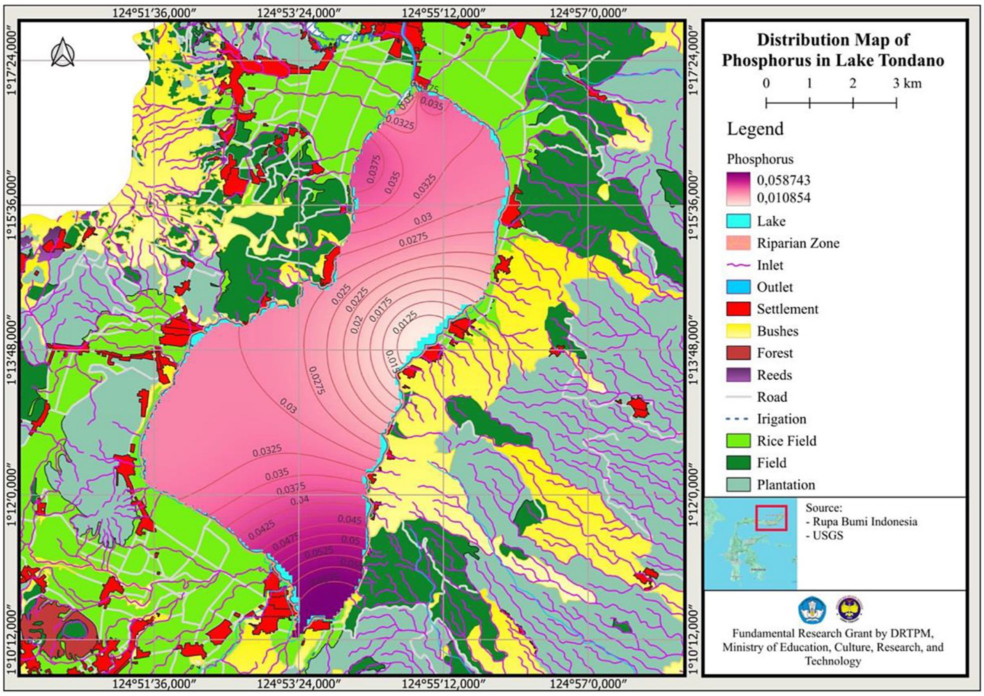


**Figure 3.** Phosphor distribution

areas. Nitrogen concentrations range from 0.05% to 0.16%, with the highest levels detected at sampling points 6 and 7. Point 6, located in agricultural areas, and point 7, which included both agricultural and residential zones, indicate that these human activities contribute to elevated nitrogen levels. Intensive agricultural activities around the lake have transported sand particles and nutrients via rivers into the lake, contributing to sediment buildup and nutrient pollution (Sinolungan et al., 2008). Prior research conducted by Moningka et al. (2015) noted a nitrogen content of 0.20% in the sediments of the Remboken area, classified as medium, with point 7 recording a nitrogen level of 0.15%. Based on spatial analysis conducted by Moningkey et al., (2022), it is known that Lake Tondano experiences a sedimentation rate of 4.4 cm per year.

Nitrogen in sediments can stem from various sources, including atmospheric precipitation, geological processes, livestock farming, agriculture, and domestic waste (Ghaly and Ramakhrishnan, 2015). Atmospheric nitrogen pollution can occur in the form of gases like NO, $N_2O$, and $HNO_3$, primarily resulting from industrial activities (Aneja et al., 2001). However, since Minahasa is not an industrial area, it is likely that the nitrogen found in the sediments does not originate from atmospheric sources. The livestock and agricultural sectors significantly contribute to nitrogen levels, particularly when animal waste is utilized as fertilizer (Ghaly and Ramakhrishnan, 2015). In addition, the agricultural sector is also a major source of nitrogen pollution, as nitrogen is an essential macronutrient needed to increase crop yields (Bahri, 2016; Gerakis et al., 2006). Alarmingly, research indicates that 50–75% of the nitrogen applied in agricultural practices is not absorbed by crops and is lost through leaching (Raun et al., 2002). Domestic waste also contributes to increased nitrogen, phosphorus, and potassium levels, which can trigger eutrophication in the lake. High nitrogen levels in these areas indicate significant contributions from domestic waste and fertilizers, likely flowing into the lake, which may potentially trigger eutrophication. Excessive phosphorus input is also a major cause of eutrophication, which can lead to the formation of harmful algal blooms (Grossman and Aksoy, 2018; Schindler et al., 2016).

Phosphorus levels in the sediment range from 0.01% to 0.06%, with the highest concentration found at site 3, a densely populated area. In nature, phosphorus exists in both organic and inorganic compounds, though it most commonly appears as insoluble or slightly soluble inorganic compounds (Dodds and Whiles, 2010). The primary sources of phosphorus pollution stem from human activities, notably fertilizers (79%), food additives (11%), detergents (7%), and other uses (3%) (Johnston et al., 2014). Phosphorus generally enters the environment through agricultural runoff, domestic waste, and industrial activities (Chang et al., 2021). Pesticides from agricultural runoff contribute to pollution (Konstantinou et al., 2006; Machate et al., 2023; Satiroff et al., 2021). Contaminants from agricultural land, such as fine-sized sediments (Pulley and Collins, 2019) and deliberately applied chemical compounds, for example, urea fertilizer (Glibert et al., 2005), ammonium nitrate (Burt et al., 2011), and phosphorus (Haygarth et al., 2005), can enter freshwater systems. The concentrations of nitrate and ammonia fluctuate temporally from year to year, influenced by fertilization activities in the rice fields (Wantasen and Luntungan, 2016). Like nitrogen, phosphorus is an essential nutrient; however, in excessive amounts, it can drive eutrophication. Elevated phosphorus levels can trigger algal blooms, which degrade water quality and disrupt aquatic ecosystems. Higher phosphorus concentrations in certain areas suggest pollution from agricultural waste or sediment containing high levels of phosphorus. Reducing phosphorus levels can be achieved through innovative management approaches, such as employing phytoremediation in surface waters (Chapman and Boucher, 2020).According to classifications (Janus and Vollenweider, 1981), Lake Tondano falls into the eutrophic category. Furthermore, based on Indonesia's Ministry of Environment Regulation No. 28 of 2009, Lake Tondano is categorized as a hypereutrophic lake. Hypereutrophic status indicates that the lake or reservoir contains extremely high nutrient levels, signaling significant pollution from increased nitrogen and phosphorus concentrations (Government of the Republic of Indonesia, 2001).

Overall, these findings highlight that the sediment in Lake Tondano has been influenced by human activities, raising nutrient levels and posing potential risks to water quality and the ecosystem. Mitigation efforts, such as better waste management and the application of phytoremediation using plants capable of absorbing nitrogen and phosphorus, are essential to reduce the negative impacts of eutrophication and restore the lake's ecosystem. Without action, pollution and ecosystem degradation could worsen, threatening aquatic habitats and biodiversity within the lake.

## Multipurpose riparian zone design

The design of the multipurpose riparian zone around Lake Tondano, based on a survey conducted using QGIS, recommends a buffer zone measuring 100 meters in width and 30 meters in length. This size is optimal due to the lake's proximity to agricultural activities, residential areas, and tourism activities, particularly with cafes surrounding the lake, which contribute to nutrient runoff. The width of riparian zones is a crucial factor that must be tailored to the specific conditions of each ecosystem to ensure the sustainability and biodiversity protection of the riparian area (Goebel et al., 2003; Moraes et al., 2014). A riparian zone of 3000 m² has been designated for the location at latitude 1.1745604 and longitude 124.8972748, where sediment nitrogen and phosphorus levels are recorded at 0.09% and 0.06%, respectively. These nutrient concentrations suggest significant contamination from surrounding human activities.

The riparian zone shown in Figure 4 highlights the designated "recommendation area" for restoration, where selected vegetation will be planted to improve water quality and ecological health. The nutrient concentrations in this area reflect significant contamination from nearby agricultural and residential activities, which are the primary sources of pollutants entering Lake Tondano. Based on pollutant distribution maps (Figures 2 and 3), critical points where these contaminants primarily enter the lake have been identified. These findings are essential for determining the optimal placement of riparian buffer zones, which will be strategically located in areas most vulnerable to nutrient runoff. Focusing on these high-priority zones will significantly enhance the effectiveness of riparian buffers in filtering pollutants before they reach the lake. Figure 4 provides a detailed map of the proposed riparian zone.

Based on calculations using a bioremediation calculator, the types and quantities of bioremediators suitable for a riparian zone of 3000 m² are presented in Table 3.

Based on the data collected, a comprehensive multipurpose riparian zone design has been crafted. This design spans 100 meters parallel to the lake and extends 30 meters perpendicularly from the lake's edge, tailored to the specific characteristics of each plant species involved. The proposed layout for the riparian zone is illustrated in Figure 5 below. The detailed distribution pattern of the 15 bioremediator plants used

**Table 3.** Types and quantities of bioremediators used in the riparian zone

| No. | Type of bioremediator | Quantity of bioremediator |
|---|---|---|
| 1 | *Cyperus platystylis* | 380 |
| 2 | *Leersia hexandra* Sw. | 770 |
| 3 | *Urochloa mutica* (Forssk.) T.Q. Nguyen | 317 |
| 4 | *Vigna luteola* | 129 |
| 5 | *Ischaemum latifolium* (Spreng.) Kunth | 710 |
| 6 | *Colocasia esculenta* | 393 |
| 7 | *Ipomoea aquatica* | 358 |
| 8 | *Dinebra chinensis* (L.) | 345 |
| 9 | *Phragmites australis* (Cav.) Trin. ex Steud. | 454 |
| 10 | *Diplazium esculentum* (Retz.) Sw. | 26 |
| 11 | *Ficus septica* | 45 |
| 12 | *Ludwigia octovalvis* | 304 |
| 13 | *Metroxylon sagu* | 144 |
| 14 | *Cyperus papyrus* | 60 |
| 15 | *Acrosticum aureum* L. | 29 |

to establish the riparian zone of Lake Tondano is shown in Figure 6. In developing a multipurpose riparian design around Lake Tondano, which spans an area of 3000 m², it is essential to consider the characteristics of non-invasive species, local conditions, and ecological functions of each plant species as phytoremediators. Fifteen plant species from intact riparian zones will be used in the design of a multipurpose riparian zone aimed at restoring areas with elevated nitrogen (N) and phosphorus (P) levels, as determined by our analyses. These plants not only contribute to the ecological balance of the area but also play a crucial role in improving water quality by absorbing excess nutrients and contaminants from the environment. This process considers the specific local conditions that support plant growth, including aquatic zones, semi-wet transitional areas, and dry regions. Additionally, the restoration effort involves a combination of trees, shrubs, and grasses within the riparian zone model, all aimed at enhancing water quality and promoting ecosystem health around Lake Tondano. Various types of plants—ranging from herbaceous grasses and wild plants to small woody shrubs and tall trees—will be planted, considering their physical forms and structures, which influence water runoff and the movement of pollutants, such as fine sediments. The effectiveness of buffer zones in reducing pollution heavily relies on the plant species used, as each has different capabilities in handling pollution and supporting the local ecosystem (Roberts et al., 2012).

The diversity of vegetation within this riparian zone is crucial for both bioremediation and maintaining ecosystem balance. Riparian plants in buffer zones effectively absorb pollutants, such as nitrogen and phosphorus, serving as agents for water purification in watershed areas (Yang et

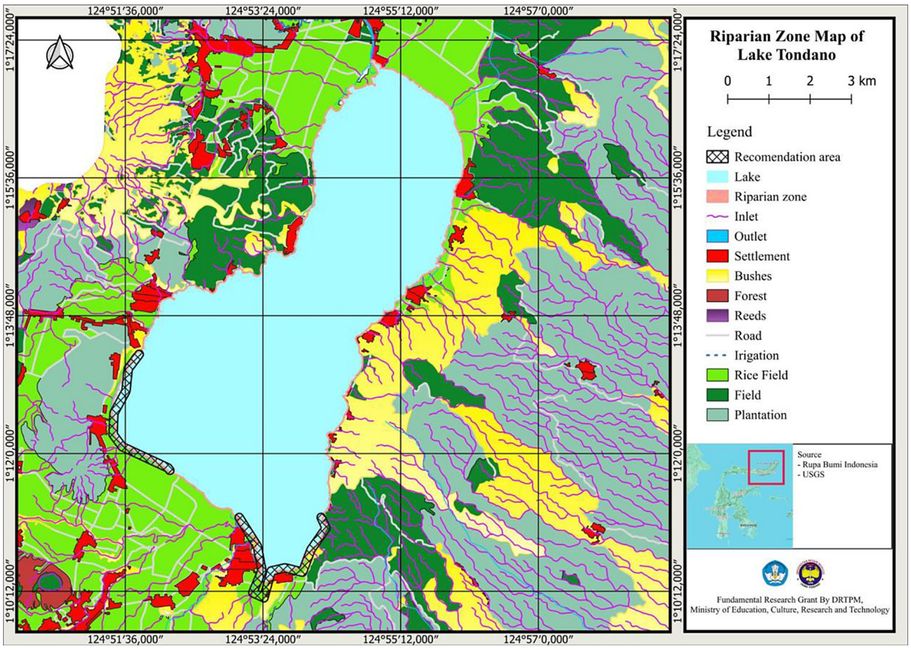


**Figure 4.** Multipurpose riparian zone design

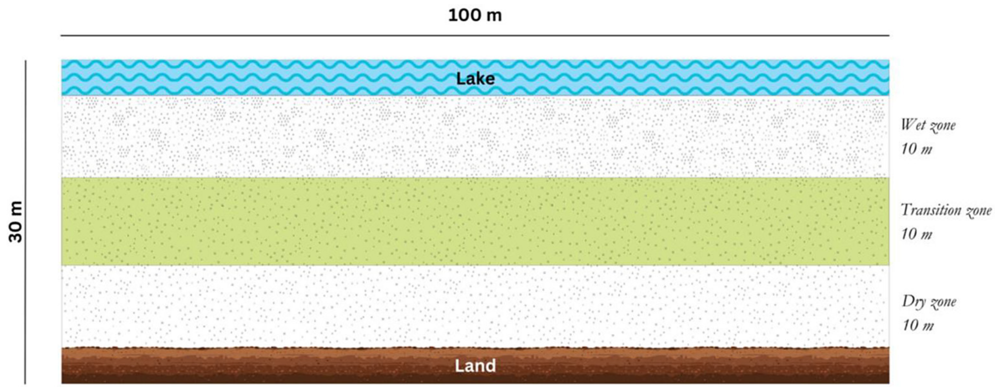


**Figure 5.** The layout of the distribution of the selected species in the riparian zone model

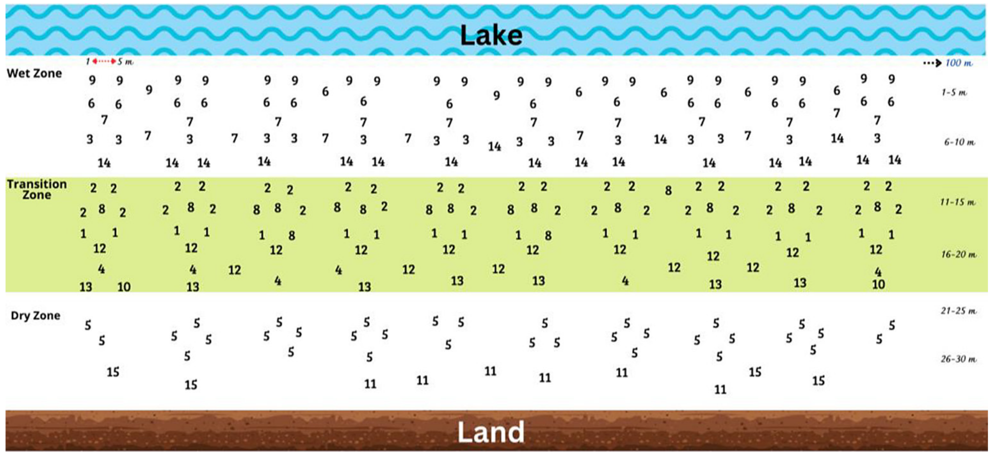


**Figure 6.** Detailed distribution of bioremediator plants in the riparian zone

al., 2014). Riparian zones are transitional areas between aquatic and terrestrial ecosystems that connect and regulate ecological functions in both habitats (Henning and Remsburg, 2009; Naiman and Décamps, 1997). Furthermore, research by Champagne et al., (2022) indicates that riparian zones can sustain trophic structures even under high agricultural intensity, emphasizing their ability to function optimally despite agricultural pressures. Additionally, riparian vegetation plays a significant role in sediment erosion and deposition processes; plants along riverbanks stabilize soil, thereby reducing erosion rates and enhancing fluvial stability (Hupp and Rinaldi, 2007).

To maximize the potential for remediation of pollutants, particularly nitrogen and phosphorus, it is critical to carefully map the riparian vegetation. This planning will ensure the successful implementation of the desired riparian design. Wet-tolerant plants, such as *Colocasia esculenta*, *Phragmites australis*, *Cyperus papyrus*, *Urochloa mutica*, and *Ipomoea aquatica*, are planted closer to the lake's edge. These species possess deep, dense root systems that can stabilize sediments, reduce erosion, and absorb excess nutrients from the water. Although *Ipomoea aquatica* is invasive, it is still utilized because its growth can be managed through daily harvesting, keeping its population under control.

In the transitional zone, plants such as *Vigna luteola*, *Cyperus platystylis*, *Dinebra chinensis*, *Ludwigia octovalvis*, and *Metroxylon sagu* are chosen for their adaptability to fluctuating moist conditions. These plants act as a bridge between the wet and dry zones, filtering flowing water and capturing nutrients before they enter the water body. In drier areas, trees like *Ficus septica* are planted, as they can access deeper water and nutrients in the soil while stabilizing areas prone to drought. This zone also includes *Ischaemum latifolium* and *Acrosticum aureum*, which contribute to remediation efforts.

The significance of plant diversity in the riparian area is underscored by its capacity to enhance the remediation of pollutants, particularly nitrogen and phosphorus. By integrating various growth forms, such as grasses, shrubs, and trees, each species contributes uniquely to nutrient absorption, soil stabilization, and erosion control. For instance, *Cyperus platystylis* and *Leersia hexandra* serve as sediment traps at the lake's edge, while *Metroxylon sagu* and *Ficus septica* help maintain ecological balance in drier areas. The arrangement of vegetation with diverse growth forms creates a natural ecosystem gradient, allowing each plant zone to filter water gradually and absorb pollutants before they reach open waters. The varied vegetation also supports natural filtration processes that can improve the quality of water entering the lake. Tree-based riparian buffers, though less effective at capturing sediment and pollutants compared to grass buffers, provide significant climate benefits such as carbon sequestration and regulating water temperatures. Combining these two types of buffers in a zoned riparian approach can enhance the overall environmental benefits, addressing multiple ecosystem services at once (Cole et al., 2020). Additionally, research indicates that although grass species excel at reducing sediment loss, both grasses and trees are crucial for maintaining soil stability and improving water quality (Dunn et al., 2022). This integration of diverse plant species is particularly vital for areas like Lake Tondano, where it not only reduces erosion and enhances biodiversity but also filters excess nutrients from runoff. Ultimately, restoring the riparian zone not only boosts biodiversity but also decreases surface runoff into rivers and lakes, effectively filtering and purifying groundwater while retaining harmful pollutants (Bahn and An, 2020).

The layout of plant species is designed meticulously, divided into three main sections: wet zone, transitional zone, and dry zone, each serving vital ecological roles. A zigzag planting system is implemented to enhance pollutant filtration efficiency, ensuring that each plant can function optimally in minimizing runoff into the lake. This pattern creates variability in nutrient absorption, prevents the dominance of a single species, and expands the absorption range of plants. The placement of vegetation is adjusted according to the moisture tolerance of each species, where more water-tolerant plants are located near the lake's edge, while drought-resistant species are planted further away. This design also accounts for topographical variations and adjusts planting based on soil and water quality analysis along the riparian zone. With this structured arrangement, the riparian model aims to establish plant groups that effectively control erosion and filter pollutants. This approach not only contributes to the health of the Lake Tondano ecosystem but also supports ecological sustainability and integrity in the face of challenges posed by human activities and environmental changes. The combination of diverse species ensures that the riparian zone functions as a robust buffer, playing a critical role in maintaining water quality and supporting biodiversity along the lake.

## CONCLUSIONS

This research successfully identified 91 plant species from 60 genera and 42 families surrounding Lake Tondano, showcasing the region's rich biodiversity. From this extensive analysis, 15 riparian plant species were selected based on their Importance Value Index (IVI), non-invasive status, and ability to purify water by absorbing nitrogen and phosphorus. These species, chosen from intact riparian zones, demonstrated resilience and adaptability. They will be integral to the design of a multipurpose riparian zone aimed at restoration efforts in areas experiencing elevated nitrogen and phosphorus levels, as determined through our rigorous analyses. The selected species include *Cyperus platystylis, Leersia hexandra* Sw., *Urochloa mutica* (Forssk.) Nguyen, *Vigna luteola, Ischaemum latifolium* (Spreng.) Kunth, *Colocasia esculenta, Ipomoea aquatica, Dinebra chinensis* (L.), *Phragmites australis* (Cav.) Trin. ex Steud., *Diplazium esculentum* (Retz.) Sw., *Ficus septica, Ludwigia octovalvis, Metroxylon sagu, Cyperus papyrus*, and *Acrosticum aureum* L.

The research was conducted at Lake Tondano, Minahasa, Indonesia, following a structured methodology consisting of three main stages: data collection, data analysis, and design. The data collection phase involved conducting a vegetation survey to document existing riparian plant species, mapping land use, and measuring nitrogen and phosphorus levels in the lake's sediments. This assessment particularly focused on areas vulnerable to human activities, such as agriculture and residential development. Utilizing QGIS analysis, a riparian zone measuring 100 × 30 m was designed at coordinates 1.1745604 latitude and 124.8972748 longitude, targeting nutrient-rich locations contributing to eutrophication.

The riparian zone design features three sections—wet, transition, and dry zones—each serving a specific ecological role. A zigzag planting pattern optimizes pollutant filtration, enabling the selected species to effectively mitigate runoff into Lake Tondano. This diverse planting strategy enhances nutrient uptake and prevents the dominance of any single species, ultimately improving the zone's capacity to filter pollutants and support ecological health.

The significance of this study lies in its potential for sustainable management of Lake Tondano's ecosystem. By addressing erosion and nutrient pollution, the proposed multipurpose riparian zone contributes to ecological health and biodiversity, serving as a model for integrating conservation efforts with pollution control strategies in other vulnerable ecosystems. The novel contributions of this study include identifying specific plant species capable of thriving in nutrient-rich sediments and quantifying their nutrient absorption capacities, thereby providing a scientifically grounded model for similar conservation efforts in vulnerable ecosystems and enhancing overall resilience. While this study focuses on the design of a riparian zone for restoration, it has limitations. Future research should assess the long-term impacts of the selected species on water quality and their role in mitigating nutrient pollution. Such investigations are crucial for enhancing the overall health of riparian ecosystems and ensuring the sustainability of Lake Tondano amidst ongoing challenges.

## Acknowledgements

This research is funded by the Directorate of Research, Technology, and Community Service, Ministry of Education, Culture, Research, and Technology of Indonesia, under the 2024 Research Program Contract (Number: 067/E5/PG.02.00.PL/2024, dated June 11, 2024), as well as the Research and Community Service Institute of Manado State University (Research Contract Number: 381/UN41.9/TU/2024).

## REFERENCES

1. Ailstock, M.S., Norman, C.M., Bushmann, P.J. 2001. Common reed Phragmites australis: Control and effects upon biodiversity in freshwater nontidal wetlands. Restoration Ecology, 9(1), 49–59. https://doi.org/10.1046/j.1526-100X.2001.009001049.x
2. Aneja, V.P., Roelle, P.A., Murray, G.C., Southerland, J., Erisman, J.W., Fowler, D., Asman, W.A.H., Patni, N. 2001. Atmospheric nitrogen compounds. II: Emissions, transport, transformation, deposition and assessment. Atmospheric Environment, 35(11), 1903–1911. https://doi.org/10.1016/S1352-2310(00)00543-4
3. Bahn, G.S., An, B.C. 2020. Analysis of environmental purification effect of riparian forest with poplar trees for ecological watershed management: A case study in the floodplain of the dam reservoir in Korea. Sustainability (Switzerland), 12(17), 1–16. https://doi.org/10.3390/SU12176871
4. Bahri, S. 2016. Identification of nitrogen (N) and phosphorus (P) pollution sources contributing to the excessive growth of aquatic plants in Lake Tempe, South Sulawesi (in Indonesia). Jurnal Sumber Daya Air, 12(2), 159–174. https://doi.org/10.32679/jsda.v12i2.63
5. Balachandran, T., Nanthakumaran, A., Devaisy, S., Sivanesan, K.S. 2018. Role of colocasia esculenta in constructed wetlands for treating rice mill wastewater. AGRIEAST: Journal of Agricultural Sciences, 12(2), 19. https://doi.org/10.4038/agrieast.v12i2.56
6. Bindu, T., Sylas, V.P., Mahesh, M., Rakesh, P.S., Ramasamy, E.V. 2008. Pollutant removal from domestic wastewater with Taro (*Colocasia esculenta*) planted in a subsurface flow system. Ecological Engineering, 33(1), 68–82. https://doi.org/10.1016/j.ecoleng.2008.02.007
7. Burt, T.P., Howden, N.J.K., Worrall, F., Whelan, M.J., Bieroza, M. 2011. Nitrate in United Kingdom rivers: Policy and its outcomes since 1970. Environmental Science and Technology, 45(1), 175–181. https://doi.org/10.1021/es101395s
8. Champagne, E.J., Guzzo, M.M., Gutgesell, M.K., McCann, K.S. 2022. Riparian buffers maintain aquatic trophic structure in agricultural landscapes. Biology Letters, 18(3). https://doi.org/10.1098/rsbl.2021.0598
9. Chang, D., Lai, Z., Li, S., Li, D., Zhou, J. 2021. Critical source areas' identification for non-point source pollution related to nitrogen and phosphorus in an agricultural watershed based on SWAT model. Environmental Science and Pollution Research, 28(34), 47162–47181. https://doi.org/10.1007/s11356-021-13973-9
10. Chapman, K., Boucher, J. 2020. Phosphorus phytoremediation using selected wetland plants in constructed floating mats. Applied Water Science, 10(6), 1–6. https://doi.org/10.1007/s13201-020-01215-1
11. Chen, M., Zhang, X., Jiang, P., Liu, J., You, S., Lv, Y. 2022. Advances in heavy metals detoxification, tolerance, accumulation mechanisms, and properties enhancement of *Leersia hexandra* Swartz. Journal of Plant Interactions, 17(1), 766–778. https://doi.or

g/10.1080/17429145.2022.2096266

12. Coates, D. 2023. Ecosystem restoration and inland food fisheries in developing countries – opportunities for the United Nations Decade on Ecosystem Restoration 2021–2030, 1231. FAO Fisheries and Aquaculture. https://doi.org/10.4060/cc7082en
13. Cole, L.J., Stockan, J., Helliwell, R. 2020. Managing riparian buffer strips to optimise ecosystem services: A review. Agriculture, Ecosystems and Environment, 296(February), 106891. https://doi.org/10.1016/j.agee.2020.106891
14. Dodds, W.K., Whiles, M.R. 2010. Nitrogen, Sulfur, Phosphorus, and Other Nutrients. In Freshwater Ecology (2nd Ed., pp. 345–373). Academic Press. https://doi.org/10.1016/b978-0-12-374724-2.00014-3
15. Dunn, R.M., Hawkins, J.M.B., Blackwell, M.S.A., Zhang, Y., Collins, A.L. 2022. Impacts of different vegetation in riparian buffer strips on runoff and sediment loss. Hydrological Processes, 36(11), 1–13. https://doi.org/https://10.1002/hyp.14733
16. Gerakis, A., Rasse, D., Kavdir, Y., Smucker, A., Katsalirou, I., Ritchie, J. 2006. Simulation of leaching losses in the nitrogen cycle. Communications in Soil Science and Plant Analysis, 37(13–14), 1973–1997. https://doi.org/10.1080/00103620600767462
17. Ghaly, A., Ramakhrishnan, V.V. 2015. Nitrogen sources and cycling in the ecosystem and its role in air, water and soil pollution: A critical review. Journal of Pollution Effects & Control, 3(2). https://doi.org/10.4172/2375-4397.1000136
18. Glibert, P.M., Trice, T.M., Michael, B., Lane, L. 2005. Urea in the tributaries of the Chesapeake and coastal Bays of Maryland. Water, Air, and Soil Pollution, 160(1–4), 229–243. https://doi.org/10.1007/s11270-005-2546-1
19. Goebel, P.C., Palik, B.J., Pregitzer, K.S. 2003. Plant diversity contributions of riparian areas in watersheds of the Northern Lake States, USA. Ecological Applications, 13(6), 1595–1609.
20. Government of the Republic of Indonesia. 2001. Government Regulation of the Republic of Indonesia Number 82 of 2001 concerning Water Quality Management and Water Pollution Control (in Indonesia). In Peraturan Pemerintah tentang Pengelolaan Kualitas Air dan Pengendalian Pencemaran Air 1–22.
21. Grossman, A.R., Aksoy, M. 2018. Algae in a phosphorus-limited landscape. In Annual Plant Reviews online 48. https://doi.org/10.1002/9781119312994.apr0527
22. Haygarth, P.M., Condron, L.M., Heathwaite, A.L., Turner, B.L., Harris, G.P. 2005. The phosphorus transfer continuum: Linking source to impact with an interdisciplinary and multi-scaled approach. Science of the Total Environment, 344(1–3), 5–14. https://doi.org/10.1016/j.scitotenv.2005.02.001
23. Henning, B.M., Remsburg, A.J. 2009. Lakeshore vegetation effects on avian and anuran populations. American Midland Naturalist, 161(1), 123–133. https://doi.org/10.1674/0003-0031-161.1.123
24. Hupp, C.R., Rinaldi, M. 2007. Riparian vegetation patterns in relation to fluvial landforms and channel evolution along selected rivers of Tuscany (Central Italy). Annals of the Association of American Geographers, 97(1), 12–30. https://doi.org/10.1111/j.1467-8306.2007.00521.x
25. Janus, L.L., Vollenweider, R.A. 1981. The OECD Cooperative Programme on Eutrophication.
26. Johnston, A.E., Poulton, P.R., Fixen, P.E., Curtin, D. 2014. Phosphorus. Its Efficient Use in Agriculture. In Advances in Agronomy 1st ed., 123. Elsevier Inc. https://doi.org/10.1016/B978-0-12-420225-2.00005-4
27. Karouw, C.J.V., Soeryanto. 2024. Changes in land use and their impact on the environmental degradation of Lake Tondano in Minahasa Regency (Indonesia). Syntax Literate, 9(4), 1–23.
28. Konstantinou, I.K., Hela, D.G., Albanis, T.A. 2006. The status of pesticide pollution in surface waters (rivers and lakes) of Greece. Part I. Review on occurrence and levels. Environmental Pollution, 141(3), 555–570. https://doi.org/https://10.1016/j.envpol.2005.07.024
29. Kumurur, V.A. 2002. Strategic Aspects of Integrated Management of Lake Tondano (in Indonesia). Ekoton, 2(1), 73–80.
30. Li, M., Li, Y., Zhang, Y., Xu, Q., Iqbal, M. S., Xi, Y., Xiang, X. 2022. The significance of phosphorus in algae growth and the subsequent ecological response of consumers. Journal of Freshwater Ecology, 37(1), 57–69. https://doi.org/10.1080/02705060.2021.2014365
31. Lin, H., You, S., Liu, L. 2019. Characterization of microbial communities, identification of Cr(VI) reducing bacteria in constructed wetland and Cr(VI) removal ability of bacillus cereus. Scientific Reports, 9(1), 1–10. https://doi.org/10.1038/s41598-019-49333-4
32. Liu, J., Zhang, X.-H., You, S.- H., Wu, Q.-X., Chen, S.-M., Zhou, K.-N. 2014. Cr(VI) removal and detoxification in constructed wetlands planted with Leersia hexandra Swartz. Ecological Engineering, 71, 36–40. https://doi.org/10.1016/j.ecoleng.2014.07.047
33. Machate, O., Schmeller, D. S., Schulze, T., Brack, W. 2023. Review: mountain lakes as freshwater resources at risk from chemical pollution. Environmental Sciences Europe, 35(1). https://doi.org/10.1186/s12302-022-00710-3
34. Moningka, V.V., Sinolungan, M.T.M., Kaunang, D., Kawulusan, R. 2015. Physical and Chemical Properties of Sediment in Tondano Lake (in Indonesia). In Cocos, 6(9), 1–6.
35. Moningkey, A.T., Rampengan, M.M.F., Tumengkol,

A.A., Kumaat, J.C. 2022. Study of bathymetry and sedimentation in Tondano Lake. IOP Conference Series: Earth and Environmental Science, 986(1). https://doi.org/10.1088/1755-1315/986/1/012038

36. Moraes, A.B., Wilhelm, A.E., Boelter, T., Stenert, C., Schulz, U.H., Maltchik, L. 2014. Reduced riparian zone width compromises aquatic macroinvertebrate communities in streams of southern Brazil. Environmental Monitoring and Assessment, 186(11), 7063–7074. https://doi.org/10.1007/s10661-014-3911-6
37. Naiman, R.J., Décamps, H. 1997. The ecology of interfaces: Riparian zones. Annual Review of Ecology and Systematics, 28(102), 621–658. https://doi.org/10.1146/annurev.ecolsys.28.1.621
38. Pulley, S., & Collins, A. L. 2019. Field-based determination of controls on runoff and fine sediment generation from lowland grazing livestock fields. Journal of Environmental Management, 249(February). https://doi.org/10.1016/j.jenvman.2019.109365
39. Qin, B., Gao, G., Zhu, G. W., Zhang, Y., Song, Y., Tang, X., Xu, H., Deng, J. 2013. Lake eutrophication and its ecosystem response. Chinese Science Bulletin, 58(9), 961–970. https://doi.org/10.1007/s11434-012-5560-x
40. Raco, B., Wicaksono, A., Triweko, R.W. 2022. The level of erosion risk due to land cover change in the watershed area of Lake Tondano (in Indonesia). Jurnal Teknik Sipil, 11(1), 63–76.
41. Raun, W.R., Solie, J.B., Johnson, G.V., Stone, M.L., Mullen, R.W., Freeman, K.W., Thomason, W.E., Lukina, E.V. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94, 815–820.
42. Roberts, W.M., Stutter, M.I., Haygarth, P.M. 2012. Phosphorus retention and remobilization in vegetated buffer strips: A review. Journal of Environmental Quality, 41(2), 389–399. https://doi.org/10.2134/jeq2010.0543
43. Runtuwene, S.E.Y., Ratag, S.P., Lasut, M.T. 2023. Community participation of Peleloan Village in Tondano Selatan District, Minahasa Regency in Lake Tondano conservation activities (in Indonesia). 2(1), 5–9.
44. Satiroff, J.A., Messer, T.L., Mittelstet, A.R., Snow, D.D. 2021. Pesticide occurrence and persistence entering recreational lakes in watersheds of varying land uses. Environmental Pollution, 273, 116399. https://doi.org/10.1016/j.envpol.2020.116399
45. Schindler, D.W., Carpenter, S.R., Chapra, S.C., Hecky, R.E., Orihel, D.M. 2016. Reducing phosphorus to curb lake eutrophication is a success. Environmental Science and Technology, 50(17), 8923–8929. https://doi.org/10.1021/acs.est.6b02204
46. Setyono, P., Himawan, W. 2018. Analyses of bioindicators and physicochemical parameters of water of Lake Tondano, North Sulawesi Province, Indonesia. Biodiversitas, 19(3), 817–824. https://doi.org/10.13057/biodiv/d190315
47. Sinolungan, M.T.M., Soeroto, B., Kondo, F., Koumoto, T. 2008. The geochemical characteristics of sediment in Tondano Lake, Indonesia: Heavy metals and organic matter contents, and grain size distribution. Paddy and Water Environment, 6(3), 341–348. https://doi.org/10.1007/s10333-008-0132-z
48. Sittadewi, E.H. 2008. Strategic functions of Lake Tondano, Ecosystem Changes, and the Problems That Occur (in Indonesia). J. Tek. Ling., 9(1), 59–66.
49. Walangitan, H.D., Rotinsulu, W.C., Paat, F.J. 2024. analysis of management strategies for lake tondano ecosystem in north sulawesi, Indonesia using SWOT and AHP methods. Revista de Gestão Social e Ambiental, 1–20.
50. Wantasen, S., Luntungan, J.N. 2016. Spatial-temporal distribution of nitrogen in the watershed of Lake Tondano, North Sulawesi Province (in Indonesia). Bumi Lestari Journal of Environment, 16(1), 16–22. https://doi.org/10.24843/blje.2016.v16.i01.p03
51. Yang, F., Yan, Z.Y., Liu, Y.N., Han, H., Gong, W., Ni, H.W. 2014. Research on the plant selection of buffer zone and pollutants removal ability of plants in ashi river Basin. Applied Mechanics and Materials, 692, 44–49. https://doi.org/10.4028/www.scientific.net/AMM.692.44