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Nutrient Loss, and Economic Loss Due to Sedimentation in Mamasa Sub-Watershed

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Abstract- The Mamasa Subwatershed in Indonesia faces significant challenges due to soil degradation, characterized by high erosion and sedimentation rates, leading to nutrient and economic losses. This study analyzes the impact of these issues on nutrient loss and associated economic costs, focusing on nitrogen (N), phosphorus (P), and potassium (K). Sediment samples were collected from upstream, middle, and downstream areas, revealing that the upstream region experiences the highest sedimentation (6,716.21 tons/ha/year) and nutrient losses (94.02 kg N, 12.63 kg P, and 22.16 kg K per hectare annually). Economic losses due to nutrient depletion, calculated using the replacement cost of fertilizers, are estimated at IDR 4.5 billion annually for subsidized fertilizers and IDR 23.7 billion for non-subsidized fertilizers. Key contributing factors include steep slopes (25-45% and >45%), shifting cultivation, and inadequate conservation practices. This degradation significantly impacts soil fertility, reducing agricultural productivity and imposing financial burdens on farmers. The study highlights the need for integrated watershed management, emphasizing soil conservation techniques such as terracing, agroforestry, and farmer education on sustainable practices. These measures could mitigate erosion, reduce nutrient loss, and enhance soil recovery, contributing to the sustainability of the Mamasa Sub-watershed ecosystem and improving local livelihoods. This research underscores the critical need for data-driven, multidisciplinary approaches to address watershed management's ecological, economic, and social dimensions. By implementing effective strategies, stakeholders can achieve more sustainable land use and mitigate the adverse effects of soil degradation.

Keywords- Economic loss, Nutrient Loss, Sedimentation, Soil Degradation, Watershed.

I. Introduction

Soil degradation can occur due to nutrient loss, soil saturation, and erosion. This leads to decreased soil productivity and a loss of soil's ability to regulate water balance. Soil degradation is often exacerbated by deforestation and land degradation, which reduce the effective area of forest vegetation. As a result, vegetation can no longer function as a protection sub-system within the overall watershed system. One of the watersheds of concern is the Mamasa Sub-watershed, which is categorized as a priority watershed based on the Decree of the Ministry of Environment. Mamasa Sub-watershed covers a cross-province area in South Sulawesi and West Sulawesi with 104,680.52 hectares. Research by Anila et al. (2020) and Isra et al. (2023) confirmed that soil degradation in this watershed area seriously affects ecosystem function and natural resource sustainability.

The condition of the Mamasa Sub-watershed shows a significant decline in the quality and quantity of forests. This decline affects the function of the forest ecosystem and results in land degradation, especially on agricultural land. This degradation is caused by high erosion and sedimentation rates. Sedimentation is highest in the upstream area, where sedimentary materials are carried by water flow to the middle and downstream areas of the watershed. The accumulation of sedimentation affects the turbidity of river water, reduces water quality, and increases the sediment load along the watershed. Studies by (Budiati et al., 2024; Mosi et al., 2024; Saputra, 2019) show that increased sedimentation in the upstream watershed significantly affects water quality and ecosystem functions in the downstream watershed, emphasizing the importance of integrated management to mitigate its impacts.

Land clearing for crops such as maize, coffee, and cocoa and uncontrolled shifting cultivation practices in the upper Mamasa Sub-watershed increase erosion and exacerbate the loss of nutrients such as Nitrogen (N), phosphorus (P), and potassium (K) in the topsoil. Studies by (Auliyani, 2020; Hana H et al., 2021) show that such farming practices contribute significantly to accelerated erosion and land degradation. Nutrients carried by surface runoff cause a decline in soil fertility, resulting in very poor-quality agricultural land. Physically and chemically, soils in these areas lose their carrying capacity to support optimal plant growth (Mir & Patel, 2024; Silva et al., 2024)

Nutrient losses due to erosion and sedimentation affect land productivity and have significant economic implications. The concept of *replacement cost,* or the cost of replacing nutrients through fertilizer use, can be used to measure these economic losses. The cost incurred by farmers to replace lost nutrients is an actual loss that can

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be an important indicator in evaluating the extent of land degradation (Jang et al., 2021; Wang et al., 2022).

Research shows that erosion and sedimentation impacts in the Mamasa Sub-watershed are not fully understood holistically, especially in the context of economic losses caused by nutrient loss. More in-depth analysis is needed to bridge this information gap. Studies by (Hasthi et al., 2023; N. A. Jariyah, 2020) suggest that a data-driven approach is required in order to understand the relationship between sedimentation patterns and their impact on watershed ecosystems. Thus, research can focus on identifying the primary sources of erosion and sedimentation patterns and calculating replacement costs for policymaking.

Considering the various aspects of soil degradation, nutrient loss, and economic impacts, management of the Mamasa Sub-watershed must be based on comprehensive data and analysis. Gap analysis from previous research shows the need for a multidisciplinary approach to integrate ecological, economic, and social aspects. Studies such as those conducted by (Fajeriana & Ali, 2024; N. Jariyah & Pramono, 2018) support the importance of a multidisciplinary approach for successful watershed management. The results of this study are expected to be the basis for more effective and sustainable watershed management policies while improving the community's welfare around the Mamasa Sub-watershed.

Although this study provides a comprehensive overview of the impact of soil nutrient loss on the economy and ecosystems in the Mamasa sub-watershed, there are several limitations to note. First, the analysis only covers the primary nutrients (N, P, K) without considering other micronutrients affecting soil productivity. Second, calculating economic losses uses assumptions of fertilizer prices and sedimentation data that may change over time. Third, data collection was carried out at specific points, so it did not fully represent the overall conditions of the sub-watershed.

II. METHODS

The research was conducted in the Mamasa Sub-watershed, which covers two districts, namely Mamasa district and Pinrang district, which is geographically located between 3°30'00"-2°51'00 "N and 119°15'00"-119°45'00 "E, the research location can be seen in Figure 1. This watershed area, located between South Sulawesi and West Sulawesi, is where sediment and nutrient analysis were carried out for the study. Watershed boundaries is design to identify the geographical boundaries and specifics of the research location, which is critical for understanding the sedimentation patterns and nutrient loss that affect the ecosystem and agricultural productivity in this area. Sediment analysis was conducted at the Soil Chemistry and Fertility Laboratory, Department of Soil Science, Faculty of Agriculture, Hasanuddin University, Makassar, from December 2024 until completion.

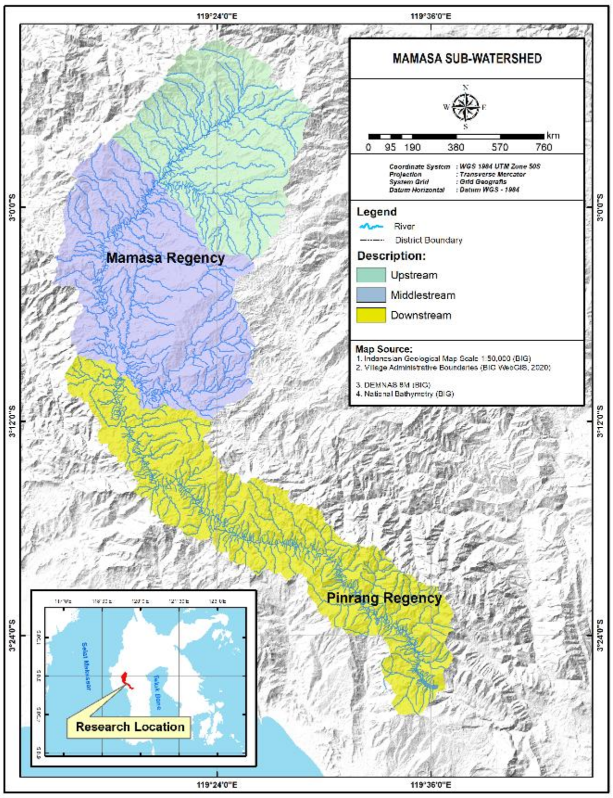

Figure 1. Research site covers the Mamasa Sub-watershed, which is located between Mamasa and Pinrang regencies, in South Sulawesi and West Sulawesi.

Sediment sampling is conducted at the location of sediment deposits, namely at Bakaru dam and outlet points in the upstream, middle, and downstream sub-watersheds. Basic sediment samples are taken and assumed to represent sediment accumulation throughout the year, in order sampling is not influenced by the season. Sediment sampling, by lowering the water sampler in a closed condition slowly and straight up to the river water level, ¾ of the depth from the water surface to the riverbed.

A. Sediment Analysis Using SWAT

The SWAT simulation process begins with the selection of the time frame to be simulated, which is done through the SWAT Run mode available in the SWAT Simulation menu. This mode allows the user to define the period for the simulation, whether it is daily, monthly, or annual, based on the specific needs of the study. Once the simulation is complete, the resulting output data can be accessed by selecting the "Read SWAT Output" option.

The data produced from the simulation is typically presented in the form of daily, monthly, or annual datasets. These options can be tailored within the simulation process to reflect the desired frequency and granularity of the output. Once the data is obtained, users can view the simulation results by navigating to the Hydrology menu or other relevant sections within the system that allow for detailed analysis of the results.

In particular, the sediment data from the SWAT simulation is of significant importance. The sediment values, which are a crucial part of the analysis, will be classified into several distinct categories. These classifications are based on the average sediment value ranges outlined in the SNI 03-1964-2008 standard. This classification process enables the data to be contextualized according to the relevant environmental and regulatory standards, providing a clearer understanding of the sediment dynamics within the studied watershed.

By utilizing these simulation and classification capabilities, researchers and environmental managers can gain valuable insights into hydrological and sediment transport processes, enabling them to make informed decisions regarding watershed management, soil conservation, and related environmental strategies.

B. Sediment Chemical Properties Analysis

Nutrients can be lost because they are in the top layer of soil, which is susceptible to erosion. Erosion always reduces soil fertility and organic matter (Jamalludin et al., 2023). If erosion continues on the soil surface, clay and humus particles and other soil particles rich in elements needed by plants will be transported (Miardini et al., 2016)

Under erosion conditions, the fine fraction of soil will be transported first and then more than the coarse fraction, so the clay content in the eroded sediment will be higher than in the original soil. This is related to the transport capacity of different surface flows to transport particles with different specific gravity. This is referred to as erosion selectivity. Erosion selectivity causes the nutrient content in the sediment to be higher than the nutrient concentration in the original soil (Pramono et al., 2024)

The analysis of sediment chemical properties to determine the nutrient content of Nitrogen, Phosphorus, and Potassium carried out consisted of N-total with the Kjeldahl method, P-available with the P-Bray method, and K-dd with the NH4OAc pH 7 method. This study did not measure the chemical properties dissolved in surface flow.

C. Economic Loss Analysis

The economic loss analysis method used in this research uses the replacement cost approach to assess nutrients lost due to erosion. Erosion not only moves soil particles but also causes the loss of nutrients in the soil. N, P, and K nutrient content in Mamasa Sub Watershed.

The amount of nutrients lost is the multiplication of the amount of soil sedimented by the proportion of the nutrient content of one ton of eroded soil.

Nutrient loss is calculated based on the volume of sedimentation that occurs in a particular area. The formula used:

$$nutrition\ loss\ \left({}^{kg}/_{ha}\right) = sed \cdot uh \qquad (1)$$

Where (1)

nutrition loss	:	The total amount of nutrients lost per hectare of soil due to erosion, this is calculated for each nutrient type (Nitrogen, Phosphorus, Potassium) (kg/ha).
sed	:	the amount of sediment that erodes and accumulates in the area per hectare per year, this sediment carries nutrients that are lost from the soil (ton/ha).
uh	:	The amount of nutrients (such as Nitrogen, Phosphorus, Potassium) in one ton of sediment, this value is calculated based on chemical analysis of sediments taken from the study area (kg/ton)

Equation (1) calculates separately for each nutrient (N, P, and K) to get a detailed picture of the extent of loss in each watershed area. The *sed* in the formula describes sedimentation (tons/ha), and the *uh* describes the Nutrient content (per ton of sediment).

The fertilizer price calculates the replacement cost to restore lost nutrients. The fertilizers used are urea fertilizer for Nitrogen (N) and NPK fertilizer for phosphorus (P) and potassium (K). Fertilizer prices can be subsidized or non-subsidized, depending on the desired calculation scenario. The agricultural land in each watershed area is obtained from remote sensing data and field surveys.

$$economic\ loss\ (IDR) = nutrient\ loss\ (kg) \cdot fertilizer\ prices\ \left({}^{IDR}/_{kg}\right) \qquad (2)$$

Where (2)

economic lost	:	Economic loss is calculated as the cost required to replace nutrient losses in the soil, this is calculated for each type of fertilizer (urea and NPK) and is calculated separately based on whether the fertilizer used is subsidized or not (IDR).
nutrient loss	:	The total amount of nutrients lost per hectare of soil due to erosion this is calculated for each nutrient type (Nitrogen, Phosphorus, Potassium) (kg/ha).
fertilizer prices	:	Price per unit of fertilizer used to replace lost nutrients (IDR/kg).

Equation (2) calculates economic losses by multiplying the nutrients lost by the relevant fertilizer price. This calculation is done for each type of fertilizer and added up to get the total economic loss.

This study also includes a sensitivity analysis to changes in fertilizer prices to increase the validity of calculating economic losses. This analysis uses a scenario of a 10%, 20%, and 30% increase and decrease in fertilizer prices from the initial price (for subsidized and non-subsidized fertilizers). This sensitivity is designed to identify how much fertilizer price variability can affect the estimation of economic losses due to soil nutrient depletion.

III. Results and Discussion

Sediment *yield* is the amount of sediment derived from erosion in the catchment area measured over a specific period and place. The following is the broad distribution of sedimentation values in the Mamasa Sub-watershed in Table 1. The high level of sedimentation in the Mamasa

Sub-watershed results in siltation of the river, narrowing of the river line, changes in flow, and flooding due to the low river floor.

Sedimentation in the Mamasa Sub-watershed results from an erosion process that carries soil and particles to the water body with a slowed water velocity level. Based on data from SWAT modeling, sedimentation in the Mamasa Sub-watershed is divided into five classes based on intensity. The upstream area shows the highest sedimentation value, especially in Mamasa and Sesenapadang sub-districts, with most of the area belonging to the high sedimentation class (class 2 to class 5). This condition causes turbidity of river water, which can have a negative impact on ecosystems and water quality (Isra et al., 2023)

Table 1 . Sedimentation of the Mamasa Sub-watershed area.

No.	Sedimentation Value (tons/ha)	Watershed Area						Total (ha)	%
		Upstream		Middle		Downstream			
		Area (ha)	%	Area (ha)	%	Area (ha)	%		
1	<10	562,59	2	4.615,68	12	15.114,92	39	20.293,18	20
2	10-250	23.331,42	84	33.479,04	88	23.760,68	61	80.571,14	79
3	251-450	2.081,26	8	0	0	0	0	2.081,26	4
4	450-1000	0	0	0	0	0	0	0,00	0
5	>1000	1.733,33	6	0	0	0	0	1.733,33	2
	Total	27.708,60		38.094,72		38.875,60		104.680,52	100

In the middle and lower reaches of the Mamasa Sub-watershed, sedimentation results not only from local erosion but also from the accumulation of sediment carried from the upstream areas. The sediment load increases as the water flows downstream, creating significant pressure on the entire watershed system. Sub-districts such as Balla and Sumarorong in the central region, along with Lembang in the downstream area, exhibit substantial sedimentation values, with most of the sedimentation classified as class 2 and class 3, indicating moderate to high levels of deposition. This sediment accumulation is a direct consequence of both natural erosion processes and human activities such as agriculture and land clearing in the upper watershed.

The accumulation of sediment throughout the watershed has far-reaching effects on the river's health and hydrology. As sediment builds up, it leads to river siltation, which significantly reduces the depth and flow capacity of rivers. Over time, this siltation causes stream constriction, narrowing the riverbed and restricting the movement of water. These changes in river flow patterns exacerbate the already vulnerable situation in the downstream areas, as the reduced flow capacity results in increased flooding risks, especially during heavy rainfall or periods of intense runoff. (Isra et al., 2023).

The amount of N, P, and K nutrients lost as a result of being carried away by erosion and surface flow, which is then sedimented in the river, obtained from the analysis of sediment samples in the upstream, middle, and downstream areas of the subwatershed, is presented in Table 2.

Table 2. Results of nutrient analysis of N, P, and K in river sediment samples

Watershed Area	Nutrient Analysis Results			Nutrients (1 ton of soil)		
	K (Cmol/kg)	P (ppm)	N (%)	K (gram)	P (gram)	N (kg)
Upstream	0,25	18,65	0,14	25	18,65	1,4
Middle	0,31	23,48	0,08	31	23,48	0,8
Downstream	0,33	18,82	0,14	33	18,82	1,4
Total	0,89	60,95	0,36	89	60,95	3,6

Nutrients lost through runoff and erosion are the product of the runoff volume and the runoff's nutrient content, as well as the product of the weight of eroded sediment and the sediment's nutrient content. Based on the Table, the N-total nutrient element is more significant than the nutrients P and K in 1 ton of soil in each Sub-watershed area; this is because, in addition to the use of NPK fertilizer, farmers also apply urea fertilizer on agricultural land. This is in response to the statement (Palacino et al., 2024), which states that Nitrogen levels in the soil vary depending on the management and use of the land because the element N in the soil is *mobile*. In addition, N can be sourced from applying urea fertilizer, while N loss can occur through denitrification, volatilization, crop transport, leaching, and soil surface erosion. Nutrient losses per hectare of agricultural land are shown in Table 3.

Table 3. Nutrient losses per hectare on agricultural land

Watershed Area	Sediment (tons/ha/year)	Nutrients (1 ton of soil)			Total Nutrient Loss (tons/ha)		
		K (gram)	P (gram)	N (kg)	K (kg)	P (kg)	N (kg)
Upstream	6716,21	25	18,65	1,4	22,16	12,63	94,02
Middle	4872,06	31	23,48	0,8	15,1	11,43	38,97
Downstream	1445,83	33	18,82	1,4	36,14	26,96	20,24
Total	13034,1	89	60,95	3,6	73,4	51,02	153,23

In the upper and middle sub-watershed areas, N nutrient loss is the largest nutrient loss compared to P and K nutrients. Variations in Nitrogen content in the soil occur due to changes in topography. The slope influences the difference in Nitrogen content. This is by the statement put forward by (Putri, 2021) that the amount of soil loss causes the low Nitrogen in the soil to a steeper slope through erosion. According to (Sundari, 2022) nutrient loss is dominated by N because this nutrient has high mobility. Nitrogen loss through erosion has a significant impact because Nitrogen is concentrated at the top of the soil profile in larger quantities than other nutrients (Amprin et al., 2020).

Erosion leads to the loss of essential nutrients in the soil, which in turn results in reduced soil productivity and compromised agricultural output. The loss of nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K) can significantly impact crop yields and soil health. To quantify the economic impact of these nutrient losses, the cost of purchasing fertilizers to restore soil fertility is often used as a metric (Bindraban et al., 2019; N. A. Jariyah, 2019).

The nutrients analyzed in these studies, specifically N, P, and K, are critical for plant growth and development. Nitrogen is essential for vegetative growth, phosphorus supports root development and flowering, and potassium contributes to overall plant health and resistance to diseases. When these nutrients are washed away due to erosion, it is necessary to replace them to maintain soil fertility and ensure sustained agricultural productivity.

The cost of replacing the lost nutrients is approximated by the cost of purchasing commonly used fertilizers, such as Urea fertilizer for nitrogen and NPK (Nitrogen, Phosphorus, Potassium) fertilizers for a broader spectrum of nutrient replenishment. These costs provide a practical way to assess the economic consequences of soil erosion, highlighting the need for effective soil conservation measures to prevent nutrient loss and safeguard agricultural investments. This method also underscores the importance of understanding the financial implications of soil erosion and its impact on sustainable farming practices.

The cost of replacing nutrient losses in the research area when using subsidized NPK and urea fertilizers is presented in Table 4. The cost of replacing nutrient losses in the study area when using NPK fertilizer and non-subsidized urea is presented in Table 5.

Table 4. Cost of replacing nutrient losses (subsidized fertilizer use)

Watershed Area	Agricultural Land Area (ha)	Total Nutrient Loss (kg)	NPK fertilizer (IDR)	Urea fertilizer (IDR)
Upstream	24.936,2	668.027	1,536,461,395	1,097,101,986
Middle	32.783,62	405.927	933,632,284	543,400,018
Downstream	38.938,13	904.183	2,079,621,273	494,078,488
Total	96.657,95	1.978.137	1,536,461,395	2,134,580,493

Table 5. Economic losses due to nutrient loss (non-subsidized fertilizer use)

Watershed Area	Agricultural Land Area (ha)	Total Nutrient Loss (kg)	NPK fertilizer (IDR)	Urea fertilizer (IDR)
Upstream	24.936,2	668.027	8,016,320,321	4,388,407,945
Middle	32.783,62	405.927	4,871,124,960	2,173,600,073
Downstream	38.938,13	904.183	10,850,197,946	1,976,313,953
Total	96.657,95	1.978.137	23,737,643,227	8,538,321,971

The economic loss value of Mamasa Sub-watershed is the sum of the cost of nutrients lost due to erosion and the area of agricultural land in each watershed area. Agricultural land used in the upstream and middle areas of the Mamasa watershed includes corn, mixed gardens, and rice fields. For the downstream area of the Mamasa watershed, the land use consists of corn, cocoa, coffee, mixed gardens, and rice fields. The analysis of economic losses using agricultural land area assumed that fertilizer use is only on agricultural land. The analysis results show that the value of economic losses in the Mamasa Sub Watershed for subsidized fertilizers is 4.5 billion IDR per year for using NPK fertilizers and 2.1 billion IDR per year for using urea fertilizers. The economic loss if using non-subsidized NPK fertilizer is 23.7 billion IDR annually, and 8.5 billion IDR per year for the use of urea fertilizer.

Increased fertilizer costs due to the loss of soil nutrients put significant economic pressure on smallholder farmers in the Mamasa Sub-watershed. Data shows that the loss of N, P and K nutrients requires additional expenditure on fertilizer purchases, both subsidized and unsubsidized. For example, the value of economic losses reaches IDR 4.5 billion per year for subsidized fertilizers and jumps to IDR 23.7 billion per year for non-subsidized fertilizers.

The results of the sensitivity analysis show that changes in fertilizer prices have a significant impact on the calculation of economic losses. With a 10% increase in fertilizer prices, economic losses in the Mamasa Sub-Watershed increased from IDR 4.5 billion to IDR 4.95 billion for subsidized fertilizer, and from IDR 23.7 billion to IDR 26.07 billion for non-subsidized fertilizer. Conversely, a 10% decrease in fertilizer prices reduces losses to IDR 4.05 billion for subsidized fertilizers and IDR 21.33 billion for non-subsidized fertilizers. This trend is even more evident with more significant price increases or decreases (20%-30%). This analysis shows that fertilizer prices are a sensitive factor in determining the economic burden on small farmers. Therefore, fertilizer subsidy and price stabilization policies are important to minimize the risk of more significant economic losses for farmers (Sundari, 2022).

Nutrients lost per hectare of land is the result of multiplying the nutrient content in 1 ton of soil by the amount of sedimentation value on agricultural land, where the largest sedimentation on agricultural land is in the upstream area of the Sub-watershed. The value of sedimentation due to erosion is strongly influenced by the level of slope and land cover, where the level of slope in the Mamasa Sub-watershed is dominated by slopes of 25-45% (steep) and >45% (very steep). Primary and secondary forests dominate land cover in the upstream area, although the land cover area is the smallest compared to the middle and downstream watershed areas. This is due to the conversion of primary and secondary forest land into land. Nutrients can be lost because they are in the top layer of soil, prone to erosion. Erosion always reduces soil fertility and organic matter (Mirzabaev et al., 2023). If erosion continues on the soil surface, clay and humus particles and other soil particles rich in elements needed by plants will be transported (Tapas et al., 2024).

The most significant loss of K-available and P-available nutrients is in the downstream area of the sub-watershed. Potassium nutrients are easily leached because high rainfall in wet tropical areas causes many K nutrients to be lost. Soils in the wet tropics develop in climatic conditions with high yearly rainfall. This situation encourages a decrease in soil base cations such as Ca, Magnesium, and K levels and increases soil acidity. In wet climate areas with high rainfall and Inceptisol soil properties that cause the availability of Ca, Magnesium, and K elements to tend to be low and increase soil acidity is a problem in itself (Hana H et al., 2021).

One of the sources of Potassium nutrients is the application of NPK fertilizer on agricultural land where the downstream area of the Sub Watershed is dominated by agricultural land such as rice fields and mixed gardens with corn, cocoa, and coffee vegetation. However, farmers have not applied SP36 and Phonska fertilizers as phosphorus and potassium nutrient enhancers. Potassium's soluble nature makes it sensitive to the effects of leaching or easily washed away by erosion and surface runoff. K^+ ions are very difficult to precipitate, so when not utilized by plants, K^+ ions will be quickly washed out of the soil (Hana H et al., 2021). A lot of phosphorus content in the soil will produce weak bonds, causing it to be easily washed away so that Phosphorus nutrient loss is influenced by erosion. The higher the erosion, the higher the phosphorus loss. Phosphorus loss is not only transported through sediment but also transported in surface flow (Chen et al., 2020). Nutrient losses of P-available and K-available are more significant in eroded soils because phosphorus and potassium are immobile, so they are bound in the soil sorption complex.

The management of the Mamasa Sub-watershed requires a comprehensive and integrated approach that addresses various ecological, economic, and social factors. To effectively mitigate the challenges posed by soil degradation and nutrient loss, a combination of land rehabilitation, erosion control, and land use optimization strategies is essential. The implementation of sustainable land management practices is not only crucial for restoring soil health but also for ensuring the long-term sustainability of agricultural productivity and the preservation of natural resources. Studies by Prima et al., (2021) show that one key solution to reducing erosion rates in the region is the adoption of soil conservation technologies. Practices such as terracing and agroforestry have proven to be effective in controlling soil erosion, particularly in areas with steep slopes like those found in the Mamasa Sub-watershed. Terracing, for instance, helps to slow down the movement of water and sediment, which reduces the speed of erosion while also improving water infiltration. On the other hand, agroforestry systems, which integrate trees and shrubs with crops, offer multiple benefits by stabilizing soil with their root systems, reducing wind erosion, and promoting biodiversity. these conservation technologies can significantly reduce erosion rates by up to 40%, particularly in areas with similar topographic conditions to those found in the Mamasa Sub-watershed.

The negative impacts of sedimentation in the Mamasa Sub-watershed are not limited to environmental degradation but also extend to the local communities who rely on the watershed for their livelihoods. Flooding resulting from silted rivers can destroy crops, erode agricultural land, and damage infrastructure, leading to significant economic losses. Moreover, the sedimentation of rivers impacts water quality, which is critical for drinking, irrigation, and aquatic ecosystems (Hana H et al., 2021).

Severe soil degradation increases the need for fertilizer use to restore fertility levels. Farmers in this region face great economic pressure due to the additional cost of purchasing fertilizers. A study by (Ary Wibisono et al., 2016) shows that the increase in fertilizer cost can reach 30% of the total production cost due to soil degradation. This phenomenon reduces their income and creates a cycle of poverty that is difficult to overcome. More significant expenditure to improve soil fertility makes farmers more vulnerable to economic losses, threatening the sustainability of their farming businesses.

For smallholder farmers, increased fertilizer costs can consume up to 30% of total production costs, previously squeezed by thin profit margins. As a result, additional expenditure to restore soil fertility is often unaffordable. This reduces their net income and forces them to reduce investments in other inputs, such as quality seeds or farm equipment. A further decline in crop yields creates a cycle of poverty that is difficult to break (Ary Wibisono et al., 2016). Reliance on non-subsidized fertilizers at much higher prices exacerbates the economic instability of smallholders, especially in areas with steep topography and high erosion rates. Therefore, an integrated management strategy focusing on soil conservation and reducing farmers' financial burden is urgently needed to improve their economic sustainability.

Given the magnitude of these challenges, it is clear that integrated watershed management is urgently needed to address the sedimentation issue. A holistic approach that combines soil conservation techniques in the upstream areas with effective river management strategies in the downstream regions is essential. For example, practices such as reforestation, agroforestry, and terracing can help reduce soil erosion in the upper reaches of the watershed, thus minimizing the amount of sediment being carried downstream (Jamaluddin et al., 2023). Additionally, the implementation of sediment management techniques, such as dredging or the creation of sediment traps, can help manage sediment accumulation in critical areas.

Land use planning and community involvement in the management process are crucial for ensuring that sustainable practices are adopted throughout the watershed. Farmers and local communities should be educated about the importance of reducing erosion through sustainable agricultural practices, such as crop rotation, reduced tillage, and the use of cover crops. These efforts can be supported by local governments through the implementation of policies that incentivize conservation practices and improve land use in sensitive areas (Arfadly, 2024).

Furthermore, land use optimization plays a pivotal role in reducing environmental stress. By promoting sustainable agricultural practices, such as crop rotation, reduced tillage, and the use of organic fertilizers, farmers can improve soil fertility and reduce their reliance on chemical inputs. These practices contribute to the long-term health of the soil, enhance its ability to retain water, and reduce the occurrence of nutrient runoff into water bodies. The education and capacity-building of farmers are crucial components of this strategy. Through training programs and workshops, farmers can be equipped with the knowledge and skills necessary to implement sustainable farming techniques that minimize the negative impact on the environment. Empowering local communities with this knowledge can also lead to greater adoption of soil conservation practices, as it helps farmers understand the long-term benefits of preserving their land (Hasthi et al., 2023).

In addition to agricultural practices, the integration of water management systems such as proper irrigation techniques and watershed management plans is vital. Implementing rainwater harvesting systems and controlling water flow through proper channeling can help maintain the watershed's hydrological balance, thereby reducing soil erosion and enhancing agricultural productivity (Hassan et al., 2024). The socio-economic aspect is equally important, as the adoption of sustainable practices can directly affect the livelihoods of local farmers. Studies have shown that the implementation of conservation measures, while requiring initial investment, often results in higher long-term agricultural yields, reduced costs of fertilizers, and lower dependency on external resources. By fostering a more sustainable farming system, the community not only benefits from improved soil health and crop productivity but also experiences reduced vulnerability to climate change impacts (Soma & Kubota. 2018).

Overall, managing the Mamasa Sub-watershed requires a holistic, multi-disciplinary approach that integrates land rehabilitation, sustainable farming practices, and community education. By focusing on soil conservation, erosion control, and land use optimization, this approach will not only safeguard the environmental integrity of the region but also contribute to the economic resilience of local communities. This integrated strategy will ultimately ensure the sustainable management of the watershed, benefiting both the environment and the people who rely on it for their livelihoods (Ziem, 2021).

IV. Conclusion

Soil degradation in the Mamasa Sub-watershed has led to significant nutrient losses, especially in the upstream areas, where sedimentation rates have reached 6,716.21 tons/ha/year. This results in the loss of essential nutrients such as 94.02 kg of Nitrogen (N), 12.63 kg of Phosphorus (P), and 22.16 kg of Potassium (K) per hectare annually. The economic impact of these losses is substantial, with the cost of replacing the nutrients using subsidized NPK fertilizer amounting to 1,536,461,395 IDR per year, which increases to 8,016,320,321 IDR if non-subsidized fertilizers are required. This situation is exacerbated by shifting cultivation practices, particularly in areas with steep slopes (25-45% and >45%), which further accelerate soil erosion and nutrient depletion. As a result, agricultural productivity in the region is severely impacted, leading to financial strain for farmers. Integrated watershed management is essential. Implementing soil conservation techniques, such as terracing and agroforestry, can significantly reduce erosion rates and improve soil fertility, reduced tillage, will help mitigate further nutrient loss and reduce the dependency on costly fertilizers. By adopting these strategies, it is possible to restore the ecological balance of the Mamasa Sub-watershed and secure the livelihoods of the local farming communities.

REFERENCES

Amprin, A., Abdunnur, A., & Masruhim, M. A. (2020). Kajian Kualitas Air dan Laju Sedimentasi Pada Saluran Irigasi Bendung Tanah Abang Di Kecamatan Long Mesangat Kabupaten Kutai Timur. *Jurnal Pertanian Terpadu*, *8*(1), 105–118. https://doi.org/10.36084/jpt..v8i1.233

Arfadly, A. R., Zubair, H., Mahyuddin, & Soma, A. S. (2024). Socio-economic vulnerability level in the Jeneberang watershed in Gowa Regency, South Sulawesi Province, Indonesia. *Regional Sustainability*, *5*(1), 100113. https://doi.org/10.1016/j.regsus.2024.03.007

Ary Wibisono, M., Hastuti, S., Endar Herawati Program Studi Budidaya Perairan Jurusan Perikanan Fakultas Perikanan dan Ilmu Kelautan, V., Diponegoro Jl Soedarto, U., & Jawa, S. (2016). Production of Daphnia sp. which Cultured with Combined Tofu Waste and Animal Feces in Fertilizer Based on Fermented Bread Waste. *Journal of Aquaculture Management and Technology*, *6*(3), 187–196. http://ejournal-s1.undip.ac.id/index.php/jamt

Auliyani, D. (2020). Upaya Konservasi Tanah dan Air pada Daerah Pertanian Dataran Tinggi di Sub-Daerah Aliran Sungai Gandul. *Jurnal Ilmu Pertanian Indonesia*, *25*(3), 382–387. https://doi.org/10.18343/jipi.25.3.382

Bindraban, P. S., van der Velde, M., Ye, L., van den Berg, M., Materechera, S., Kiba, D. I., Tamene, L., Ragnarsdóttir, K. V., Jongschaap, R., Hoogmoed, M., Hoogmoed, W., van Beek, C., & van Lynden, G. (2012). Assessing the impact of soil degradation on food production. *Current Opinion in Environmental Sustainability*, *4*(5), 478–488. https://doi.org/https://doi.org/10.1016/j.cosust.2012.09.015

Budiati, L., Hasthi, S., & Elizabeth, M. (2024). LOW-IMPACT DEVELOPMENT OF WATERSHED MANAGEMENT: A SUSTAINABILITY REVIEW ON GARANG RIVER WATERSHED IN SEMARANG CITY, INDONESIA. *Environmental Engineering and Management Journal*, *23*, 2341–2352. https://doi.org/10.30638/eemj.2024.188

Chen, L., Liu, D.-F., Song, L.-X., Cui, Y.-J., & Zhang, G. (2020). Characteristics of nutrient loss by runoff in sloping arable land of yellow-brown under different rainfall intensities. *Huan jing ke xue= Huanjing kexue / [bian ji, Zhongguo ke xue yuan huan jing ke xue wei yuan hui "Huan jing ke xue" bian ji wei yuan hui.]*, *34*, 2151–2158.

Fajeriana, N., & Ali, A. (2024). The Role of Local Communities in Implementing Soil and Water Conservation Practices for Sustainable Food Production Enhancement in the Salawati District, Sorong Regency. *Jurnal Penelitian Pertanian Terapan*, *24*(1), 134–147. https://doi.org/10.25181/jppt.v24i1.3402

Hana H, Suwardi, & Purwandaru W. (2021). Kajian Tingkat Sedimen Terlarut Dan Material Nutrien (N Dan P) Pada Perkebunan Dan Pertanian. *Seminar Nasional Biologi*, *9*, 42–47.

Hassan, Z., Khan, F. Z. A., Aldosary, A. S., Al-Ramadan, B., Ahmad, A., Manzoor, S. A., & Rahman, M. T. (2024). Roots to roofs: Farmers' perceived socio-ecological impacts of converting mango orchards to urban areas in Multan, Pakistan. *Environmental Challenges*, *15*(May), 100935. https://doi.org/10.1016/j.envc.2024.100935

Hasthi, S., Budiati, L., & Setiadi, R. (2023). Identifikasi Kondisi Eksisting Dan Dampak Sedimentasi Pada Sungai Kreo Dan Kaligarang Kota Semarang. *Saintifika*, *24*(2), 95. https://doi.org/10.25037/saintifika.v24i2.133

Isra, N., Arsyad, U., & Chairuddin, Z. (2023). Sedimentation analysis using SWAT model (soil and water assessment tool) in Mamasa Sub-Watershed. *IOP Conference Series: Earth and Environmental Science*, *1230*(1). https://doi.org/10.1088/1755-1315/1230/1/012027

Jamalludin, J., Riduansyah, R., & Krisnohadi, A. (2023). Studi Karakteristik Das Dan Kualitas Air Untuk Irigasi Pada Sub Daerah Aliran Sungai (Das) Tayan Bagian Hilir Kabupaten Sanggau. *Jurnal Sains Pertanian Equator*, *12*(4), 892. https://doi.org/10.26418/jspe.v12i4.66878

Jang, W. S., Neff, J. C., Im, Y., Doro, L., & Herrick, J. E. (2021). The Hidden Costs of Land Degradation in US Maize Agriculture. *Earth's Future*, *9*(2), 1–19. https://doi.org/10.1029/2020EF001641

Jariyah, N. A. (2019). Evaluation of Socio Economic Performance of the Brantas Watershed Based on Aplication of P61/Menhut-Ii/2014. *Jurnal Penelitian Sosial dan Ekonomi Kehutanan*, *16*(2), 95–114. https://doi.org/10.20886/jpsek.2019.16.2.95-114

Jariyah, N. A. (2020). Analisis Aspek Sosial Ekonomi Untuk Mendukung Pengelolaan DAS Moyo, Kabupaten Sumbawa, Nusa Tenggara Barat. *Jurnal Penelitian Kehutanan Faloak*, *4*(2), 95–114. https://doi.org/10.20886/jpkf.2020.4.2.95-114

Jariyah, N., & Pramono, I. (2018). KERENTANAN SOSIAL EKONOMI DAN BIOFISIK DAERAH ALIRAN SUNGAI SOLO (Socio-economic and biophysical vulnerability of Solo Watershed). *Jurnal Penelitian Pengelolaan Daerah Aliran Sungai*, *2*(2), 89–110. https://doi.org/10.20886/jppdas.2018.2.2.89-110

Miardini, A., Gunawan, T., & Murti, S. H. (2016). Kajian Degradasi Lahan Sebagai Dasar Pengendalian Banjir Di Das Juwana. *Majalah Geografi Indonesia*, *30*(2), 134. https://doi.org/10.22146/mgi.15633

Mir, A. A., & Patel, M. (2024). A Comprehensive Review on Sediment Transport, Flow Dynamics, and Hazards in Steep Channels. *Journal of Water Management Modeling*, *32*. https://doi.org/10.14796/JWMM.C517

Mirzabaev, A., Strokov, A., & Krasilnikov, P. (2023). The impact of land degradation on agricultural profits and implications for poverty reduction in Central Asia. *Land Use Policy*, *126*, 106530.

https://doi.org/https://doi.org/10.1016/j.landusepol.2022.106530

Mosi, Y., Warow, N., Usman, M., Bahuwa, I. C., Rosalia, N., Kadir, Z. S., Hamidun, M. S., Lihawa, F., & Dunggio, I. (2024). Analisis Erosi dan Sedimentasi di Sub Das Alo-Pohu Kesatuan Pengelolaan Hutan Vi Gorontalo. *Jurnal Sains Teknologi & Lingkungan*, *10*(2), 321–331. https://doi.org/10.29303/jstl.v10i2.616

Palacino, B., Ascaso, S., Valero, A., & Valero, A. (2024). Regeneration costs of topsoil fertility: An exergy indicator of agricultural impacts. *Journal of Environmental Management*, *369*(August), 122297. https://doi.org/10.1016/j.jenvman.2024.122297

Pramono, S. A., Hafid, H., Imran, H. Al, & Tarru, R. O. (2024). *Prediksi Sedimentasi Sungai : Studi Kasus Implementasi Teknik Lingkungan dalam Penelolaan Sumber Daya Air River Sedimentation Prediction : A Case Study of Environmental Engineering Implementation in Water Resources Management .* *7*(6), 2099–2108. https://doi.org/10.56338/jks.v7i6.5453

Prima, J., Rumambi, D. P., & Kamagi, Y. E. B. (2021). Identifikasi Teknik Konservasi Tanah Dan Air Di Kawasan Persawahan Untuk Menunjang Pengembangan Agrowisata Kabupaten Minahasa Tenggara. *Cocos*, *6*(6), 1–9.

Putri, F. A., & Statistik, B. P. (2021). *Pengaruh Degradasi Lahan Terhadap Keberlanjutan Pertanian Padi di Indonesia Hasil Survei Pertanian Terintegrasi (SITASI) 2021*. *2021*(1994), 111–116.

Richardson, C. P., & Amankwatia, K. (2019). Assessing Watershed Vulnerability in Bernalillo County, New Mexico Using GIS-Based Fuzzy Inference. *Journal of Water Resource and Protection*, *11*(02), 99–121. https://doi.org/10.4236/jwarp.2019.112007

Saputra, R. H. (2019). Kajian Erosi Dan Potensi Sedimentasi Di Das Kahayan Provinsi Kalimantan Tengah. *Jurnal Teknologi Berkelanjutan*, *8*(02), 69–76. https://doi.org/10.20527/jtb.v8i02.134

Silva, T. P., Bressiani, D., Ebling, É. D., & Reichert, J. M. (2024). Best management practices to reduce soil erosion and change water balance components in watersheds under grain and dairy production. *International Soil and Water Conservation Research*, *12*(1), 121–136. https://doi.org/10.1016/j.iswcr.2023.06.003

Soma, A. S., & Kubota, T. (2018). Landslide susceptibility map using certainty factor for hazard mitigation in mountainous areas of Ujung-loe watershed in South Sulawesi. *Forest and Society*, *2*(1 SE-Regular Research Articles), 79–91. https://doi.org/10.24259/fs.v2i1.3594

Sundari, Y. S. (2022). Kondisi Biofisik Sungai Berpengaruh Terhadap Terjadinya Banjir Pada Alur Sungai Karang Mumus Di Kota Samarinda (River To Biophysical Conditions Effect of Flood Event on the Karang Mumus River Flow in Samarinda City). *Jurnal Keilmuan Teknik Sipil*, *5*(1), 150–160.

Tapas, M. R., Etheridge, R., Tran, T. N. D., Finlay, C. G., Peralta, A. L., Bell, N., Xu, Y., & Lakshmi, V. (2024). A methodological framework for assessing sea level rise impacts on nitrate loading in coastal agricultural watersheds using SWAT+: A case study of the Tar-Pamlico River basin, North Carolina, USA. *Science of the Total Environment*, *951*(August), 175523. https://doi.org/10.1016/j.scitotenv.2024.175523

Wang, J., Hassan, M. A., Saletti, M., Chen, X., Fu, X., Zhou, H., & Yang, X. (2022). Experimental insights into the effect of event sequencing and sediment input texture on step-pool channel evolution. *Earth Surface Processes and Landforms*, *47*(2), 569–581. https://doi.org/https://doi.org/10.1002/esp.5272

Ziem Bonye, S., Yenglier Yiridomoh, G., & Derbile, E. K. (2021). 'Urban expansion and agricultural land use change in Ghana: Implications for peri-urban farmer household food security in Wa Municipality.' *International Journal of Urban Sustainable Development*, *13*(2), 383–399. https://doi.org/10.1080/19463138.2021.1915790