JOURNAL LA LIFESCI
VOL. 07, ISSUE 01 (057-068), 2026
DOI: 10.37899/journallalifesci.v7i1.3059

The Impact of Nickel Mining Activities on Watershed Hydrology and Coastal Sedimentation

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Article Info
Article history:
Received 15 December 2025
Received in revised from 7 January 2026
Accepted 2 February 2026

Keywords:
Nickel mining
Watershed Hydrology
Coastal Sedimentation
NDVI
NDTI

Abstract

Nickel mining activities in Pomalaa District, Kolaka Regency, are growing rapidly and have the potential to put pressure on the hydrological system of the Watershed (DAS) and the dynamics of sedimentation in coastal areas. The applied open-pit mining system causes extensive land clearing and reduced vegetation cover, which can increase surface runoff and soil erosion. This study aims to analyze the spatial relationship between nickel mining land clearing, watershed hydrological response, and coastal sedimentation levels during the period 2016–2025. The data used are multi- temporal Sentinel-2 Level-2A satellite images analyzed using the Normalized Difference Vegetation Index (NDVI) to identify the condition of mining land clearing and the Normalized Difference Turbidity Index (NDTI) to represent the level of sedimentation and turbidity of coastal waters. Spatial analysis was carried out based on watershed units to examine the upstream–downstream relationship between the intensity of mining land clearing and sedimentation responses in the estuarine zone. The results show that watersheds with a dominant low NDVI value tend to experience increased surface runoff and potential soil erosion, which in turn contributes to increased coastal sedimentation as indicated by relatively high NDTI values. These findings confirm a strong link between land cover changes due to nickel mining activities, watershed hydrological responses, and coastal sedimentation intensity. This research emphasizes the importance of a watershed-based approach in nickel mining environmental management and sedimentation impact mitigation efforts to maintain the sustainability of coastal ecosystems.

Introduction

Mining is the exploitation of natural resources, typically resulting in the disturbance of soil layers and the exposure of the land surface, particularly in open-pit mining systems (Widiatmaka et al., 2010). In Indonesia, the mining industry is a strategic sector that contributes significantly to the national economy. Indonesia has potential nickel reserves of approximately 2.9% of the world's total nickel reserves, ranking 8th globally, while in terms of production, it reaches approximately 8.6%, ranking 4th globally (Erfina & Sjarmidi, 2019). These conditions make nickel a leading national commodity that plays a vital role in supporting economic growth, particularly in mining- producing regions. One area with intensive nickel mining activity is Pomalaa District, Kolaka Regency, Southeast Sulawesi Province. Nickel mining activities in this region generally employ an open-pit mining system, involving massive land clearing and overburden removal (Fitriani et al., 2021). This process causes the loss of ground cover vegetation and changes in the physical properties of the soil, increasing the land's

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vulnerability to erosion. Various studies have shown that the environmental impacts of nickel mining activities are not limited to land but also extend to marine and coastal areas. Research by La Maga et al. (2025) reported that land conversion for nickel mining activities caused significant soil erosion and sedimentation at the Lapoa Dam, accompanied by pollution of irrigation water and decreased soil fertility in agricultural land. Similar findings were also reported by Agussalim et al. (2023), who demonstrated significant environmental damage due to nickel mining exploitation in Kolaka Regency, particularly in the Pomalaa, Wolo, and Lambandia areas, including the influx of sediment into marine waters, disrupting the balance of coastal ecosystems. Geographically, Pomalaa District borders directly on marine waters, so sediment material resulting from erosion on land has a high potential for transport via surface runoff and natural drainage systems (rivers) to coastal areas (Katupotha & Gamage, 2024; Fonseka & Karunarathne, 2024; Nashath et al., 2024; Purnama et al., 2025; Takwa et al., 2025). The loss of vegetation due to mining land clearings increases the volume of surface runoff, which in turn increases the capacity to transport sediment to estuaries and coastal waters. Research by Andi et al. (2024) in the Pomalaa region showed that the increase in open land areas around nickel mines correlated with the degradation of the watershed's hydrological response and an increase in sediment loads transported to rivers and estuaries (Azis et al., 2025; Kelley, 2025; Pambudi, 2025; Hyldmo et al., 2025).

The impact of sedimentation in coastal areas has significant ecological implications. High sedimentation can increase water turbidity, reduce sunlight penetration, and inhibit the photosynthesis process of marine organisms. Bégin et al. in Kolibongso et al. (2024) stated that increased sedimentation due to land clearing on land can cause stress, reduced growth, and even coral reef mortality. This situation emphasizes the importance of evaluating the quality of the aquatic environment around nickel mining areas to maintain the sustainability of coastal ecosystems (Purnama et al., 2024). Furthermore, the impact of nickel mining is also reflected in changes in vegetation cover on a regional scale. Lo et al. (2024) showed that villages in Sulawesi with nickel mining activities experienced deforestation almost twice as much as villages without mining, with a 4.4% decrease in forest cover during the period 2011–2018. This confirms that the impacts of nickel mining are not solely local, but have broad implications, increasing land clearing, potentially increasing erosion and sedimentation rates in downstream areas.

The relationship between vegetation cover and sedimentation was also confirmed by Paryono et al. (2016), who stated that the larger the vegetated area, the smaller the sedimentation area tends to be; conversely, an increase in the area of non-vegetated land is directly proportional to an increase in sedimentation. In addition, vegetation cover and rainfall are the factors that most influence the sedimentation rate. The results of research by Barus (2023) in Pomalaa waters showed an increase in areas with very low and medium vegetation density, and a decrease in areas with high vegetation density from 20,445.2 ha in 2014 to 16,943.8 ha in 2023. This condition correlates with the concentration of Total Suspended Solid (TSS) in Pomalaa waters which ranges from 78–111 mg/L, with a positive correlation ($r = 0.58$) between very low vegetation areas and increased TSS and a negative correlation ($r = -0.8$) between high vegetation areas and TSS values.

Developments in remote sensing and Geographic Information Systems (GIS) technology offer significant opportunities for monitoring changes in land cover and its impact on sedimentation spatially and temporally (Sowmiya et al., 2024; Shaikh & Birajdar, 2024; Ramaano, 2024). Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) can be used to identify changes in vegetation cover and land cover, while water turbidity indices such as

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the Normalized Difference Turbidity Index (NDTI) can be utilized to monitor sedimentation levels in coastal areas. Research by Ruzikulova et al. (2024) states that Sentinel-2 MSI imagery has the advantages of relatively high spatial resolution (10–20 m) and a fast revisit time of approximately 5 days, making it ideal for rapid monitoring of small to medium- scale areas such as agricultural, forestry, and urban areas. Although various studies have examined the impacts of nickel mining on land cover change, erosion, and water quality, most studies still focus on land areas or watershed scales, without comprehensively integrating the spatial relationship between mining land clearing, watershed hydrological response, and its implications for sedimentation in coastal areas (Ouchra et al., 2022; Quamar et al., 2023; Katkani et al., 2022; Kochanek et al., 2025; Nizamani et al., 2024). Therefore, this study is important to be conducted in Pomalaa District to analyse the spatial relationship between nickel mining land clearing, watershed hydrological characteristics, and coastal sedimentation levels in 2016-2025. The results of this study are expected to provide accurate and integrated spatial information as a basis for sustainable mining environmental management and efforts to mitigate the impacts of sedimentation in coastal areas (Lakra et al., 2024; Nizamani et al., 2024; Aikal et al., 2022).

Methods

Research Location

This research was conducted in Pomalaa District, Kolaka Regency, Southeast Sulawesi Province. This area is subject to intensive nickel mining activity and encompasses several watersheds (DAS) that drain directly into coastal areas. The watershed unit was used as an analytical framework to examine the upstream-downstream relationship between land surface changes and coastal sedimentation dynamics.

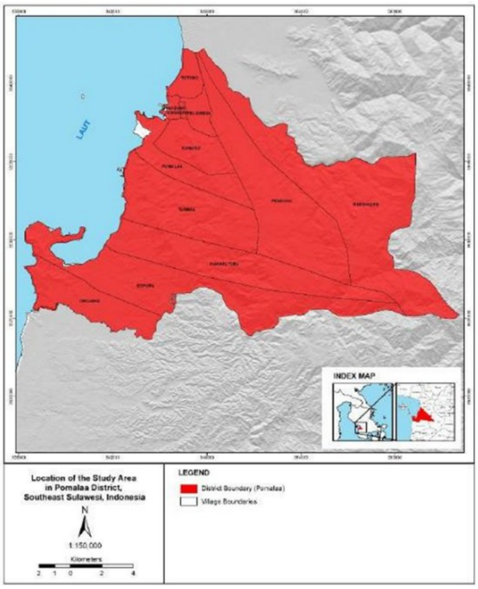

Figure 1. Research Location Map

Data

The primary data used in this study is atmospherically and radiometrically corrected Sentinel-2 Level-2A satellite imagery from 2016-2025. Supporting data includes spatial data on river basins (DAS) and spatial data on the administrative boundaries of the study area. In the context of environmental monitoring, Sentinel-2 has a relatively high spatial resolution (10–20 m) and a fast revisit time (±5 days), making it ideal for monitoring environmental changes at local to

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regional scales, including coastal areas and watersheds impacted by mining activities (Ruzikulova et al., 2024).

Analysis of Mining Land Surface Conditions and Coastal Sedimentation Mining land surface conditions related to watershed hydrological function were analyzed using the Normalized Difference Vegetation Index (NDVI) to identify and quantify the extent of nickel mining clearings in each watershed in the study area from 2016-2025, using the equation:

$$NDVI = NIR - Red$$

$$NIR + Red \ (1)$$

Classification of mining land openings uses the NDVI index from -1 to 0.25 based on the classification of the Ministry of Forestry of the Republic of Indonesia in 2012 as follows:

Table 1. Classification of NDVI Index Values

Class	NDVI Value Range	Description
1	−1.00 to −0.03	Land without vegetation
2	−0.03 to 0.15	Very low greenness
3	0.16 to 0.25	Low greenness
4	0.26 to 0.35	Moderate greenness
5	0.36 to 1.00	High greenness

Source: Ministry of Forestry of the Republic of Indonesia Number: P.12/Men hut-II/2012

Coastal sedimentation dynamics were analyzed using the Normalized Difference Turbidity Index (NDTI), which is calculated using the following equation:

$$NDTI = Red - Green$$

$$Red + Green$$

An NDTI value of less than 0 indicates clear water, while an NDTI value >0 indicates turbidity due to increased suspended sediment.

Watershed-Based Spatial Analysis

Spatial analysis was conducted by integrating the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Turbidity Index (NDTI) values using an overlay technique. Next, the area of nickel mining clearings was quantified based on the NDVI classification in each watershed, and the extent of sedimentation was quantified based on the NDTI values in the coastal zone within the watershed estuary. This approach allows for an evaluation of the relationship between vegetation cover conditions, watershed hydrological response, and their impact on downstream coastal sedimentation levels.

Results and Discussion

Physiographic, Hydrological, and Watershed Conditions of the Research Area

Pomalaa District's location in a coastal area makes it strategically important for supporting economic activity, particularly the mining sector. However, this also increases the region's vulnerability to environmental impacts, particularly those related to land degradation and coastal sedimentation. Physiographic ally, Pomalaa District has varied morphological conditions, ranging from high hills inland to lowlands in the coastal area. The inland area is generally dominated by high hills and low hills, which have the potential to generate high levels of surface runoff, especially during periods of increased rainfall. Meanwhile, the coastal area is dominated by lowlands that serve as accumulation zones for eroded material from the land.

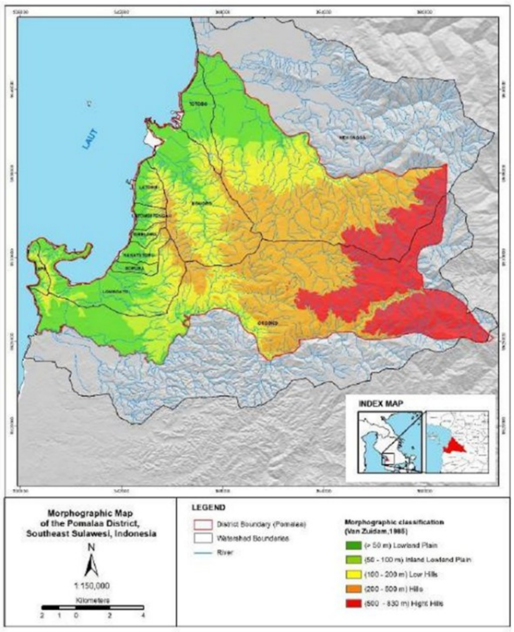

Figure 2. Morpho graphic Map of Pomalaa District

These morpho graphic conditions directly influence hydrological processes and sediment transport. Relatively steep slopes in the upstream watershed can accelerate surface runoff and increase the potential for soil erosion, especially when vegetation cover is reduced due to land clearing activities. This eroded material is then transported downstream and has the potential to accumulate in coastal areas, increasing sedimentation and water turbidity. Pomalaa District is composed of several watersheds (DAS) that flow from the mainland to the coastal areas. These watersheds act as natural systems that regulate surface water flow and serve as the main pathways for sediment transport from upstream to downstream. Watersheds in Pomalaa District are generally characterized by relatively short stream lengths with estuaries that empty directly into the sea.

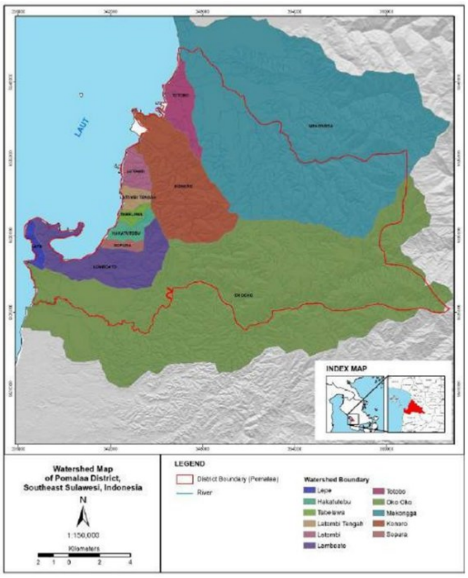

Figure 3. Watershed Map of Pomalaa District

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These conditions cause the watershed's hydrological response to changes in land use in the upstream area to be relatively rapid. Land cover changes, particularly increased land clearing, have the potential to increase surface runoff and transport sediment to rivers in a short time. Therefore, using the watershed as the unit of analysis in this study is deemed relevant to examine the relationship between changes in mining land clearing and sedimentation in coastal areas. Pomalaa District is one of the centres of nickel mining activity in Kolaka Regency. Mining activity in this area is characterized by the presence of several Mining Business Permits (IUPs) scattered throughout the sub-district. The IUP distribution map shows that part of Pomalaa District's land area is within mining concession areas, some of which overlap with the watershed. The mining system generally employed is open-pit mining, which involves extensive land clearing and stripping of overburden. This activity has the potential to reduce vegetation cover, alter the physical properties of the soil, and increase the land's vulnerability to erosion. The presence of IUPs close to the watershed network increases the potential for eroded material to be transported into rivers and then to coastal areas.

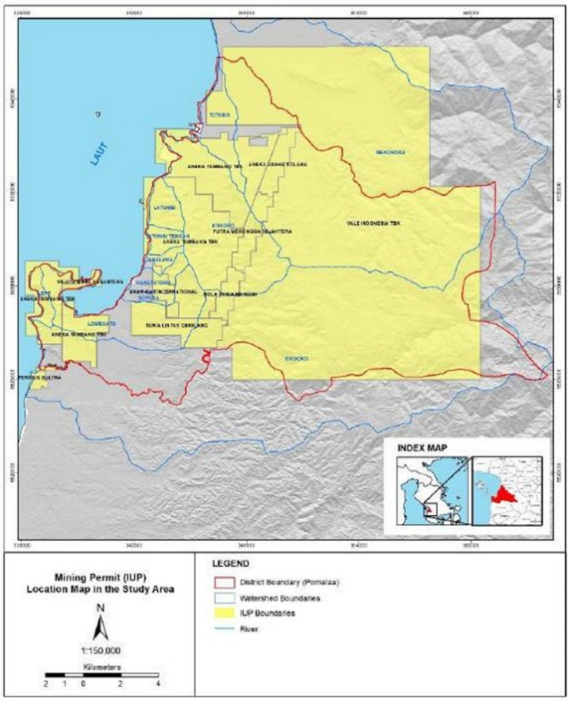

Figure 4. Location Map of Mining Permits and Watersheds in Pomalaa District Impact of Nickel Mining Activities on Watershed Hydrology and Coastal Sedimentation

The rapid expansion of nickel mining activities in Pomalaa District, Kolaka Regency, has placed significant pressure on the hydrological system of the watershed (DAS) and the surrounding coastal environment. The commonly used open-pit mining method has resulted in massive land cover changes, particularly through forest clearing and the removal of topsoil, overburden, and saprolite. These materials are loose and unconsolidated, making them highly susceptible to erosion by rainwater and wind (Prasetyo, 2024). Research results show that watershed areas in Pomalaa District dominated by mining clearings have an NDVI index value ranging from -1 to 0.25. This condition indicates the loss of cover vegetation, which can potentially increase surface runoff, allowing rainwater to flow more quickly into the river without adequate infiltration. This finding aligns with the concept of watershed hydrology, which states that vegetation cover plays a crucial role in controlling surface runoff and reducing soil erosion (Paryono et al., 2016). In nickel mining areas that employ open-pit mining systems, the overburden removal process alters the physical properties of the soil and increases its

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vulnerability to erosion (Fitriani et al., 2021). This explains why the Pomalaa watershed exhibits a hydrological response that tends to experience degradation due to mining activities.

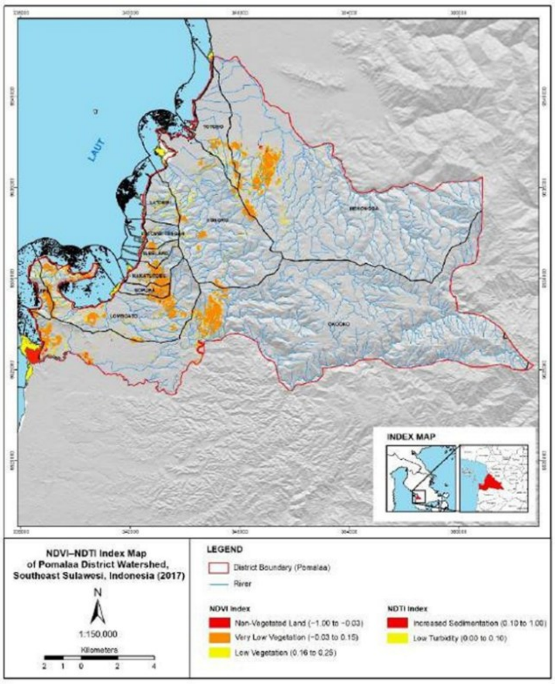

Figure 5. NDVI-NDTI Index Map for 2017 in the Pomalaa District Watershed

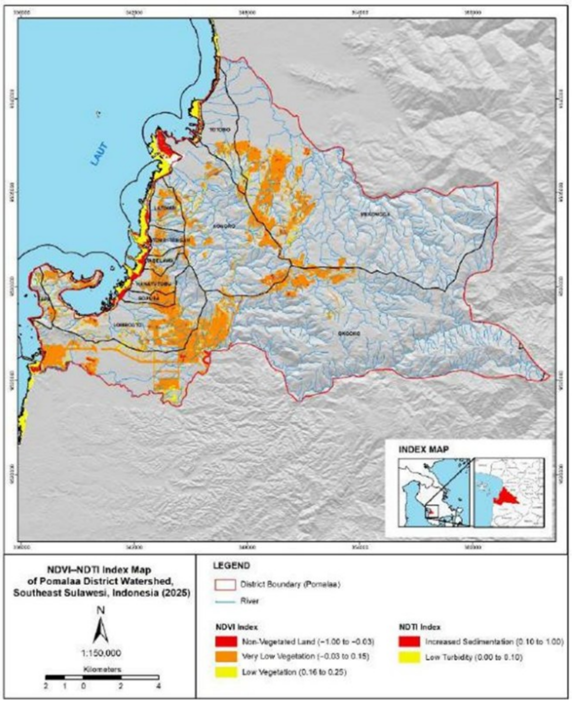

Figure 6. NDVI-NDTI Index Map for 2025 in the Pomalaa District Watershed

The results of the NDTI index analysis show that the coastal areas of the Pomalaa District watershed experiencing sedimentation have NDVI index values ranging from 0 to 1. This condition indicates the presence of suspended and sedimented sedimentary material in the coastal areas of the Pomalaa watershed and has the potential to change the morphology of the coastal area. Zahra et al. (2018), explained that continuous sediment supply can form new land

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through deposition, thereby expanding existing land. This phenomenon has implications for shoreline changes, water siltation, and disruption of coastal ecological functions, especially in areas receiving sediment flow from watersheds impacted by mining activities. Research findings in other nickel mining areas show similar impact patterns. Sangadji & Malau (2025) revealed that nickel mining activities on Gag Island triggered significant soil erosion as a result of drilling and excavation activities during the operational process. The soil particles resulting from this erosion were carried by rainwater flow towards the sea and caused increased sedimentation in the surrounding waters. This is reinforced by Steven Noris' statement in Sangadji & Malau (2025) which states that nickel mining activities on Gag Island have caused excessive sedimentation carried by surface flow towards the sea area.

Table 2. Area of Mining Land Openings and Sedimentation Based on the NDVI-NDTI Index in the Pomalaa District Watershed

Nama DAS	Indeks	Luas (Ha)									
		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Hakatutobu	NDVI (-1 sampai 0.25)	110.33	106.54	108.01	112.76	108.69	115.54	134.09	141.12	148.9	144.51
	NDTI (0 sampai 1)	18.18	31.67	37.92	16.34	12.1	13.77	24.68	37.74	48.72	57.33
Konoro	NDVI (-1 sampai 0.25)	201.91	167.81	193.7	227.47	209.5	229.17	260.87	304.78	434.17	452.74
	NDTI (0 sampai 1)	43.88	65.17	33.81	35.2	19.21	14.45	76.04	78.86	141.94	159.77
Latombi	NDVI (-1 sampai 0.25)	49.53	39.89	41	63.43	78.36	93.77	117.85	124.51	131.78	139.76
	NDTI (0 sampai 1)	8.55	16.32	28.27	16.13	4.99	6.47	56.85	38.54	78.23	83.86
Latombi Tengah	NDVI (-1 sampai 0.25)	32.44	26.51	26	25.09	21.15	24.03	37.11	49.96	62.81	66.49
	NDTI (0 sampai 1)	19	23.65	40.39	15.67	8.61	6.93	47.98	43.22	75.71	85.67
Lepe	NDVI (-1 sampai 0.25)	74.19	75.78	78.21	73.71	68.19	71.79	64.05	65.33	104.13	66.59
	NDTI (0 sampai 1)	0.74	0.73	1.68	0.44	0.31	0.09	1.23	1.86	14.68	2.54
Lomboato	NDVI (-1 sampai 0.25)	379.24	340.66	377.78	373.62	331.71	339.8	359.02	408.33	490.18	641.92
	NDTI (0 sampai 1)	20.5	35.4	46.58	14	4.37	6.13	41.95	69.09	67.69	79.35
Mekongga	NDVI (-1 sampai 0.25)	466.94	338.19	349.45	455.21	420.69	475.89	540.78	595.13	739.99	863.97
	NDTI (0 sampai 1)	11.43	21.65	4.59	0.01	-	-	26.73	97.58	1.83	37.08
Okooko	NDVI (-1 sampai 0.25)	644.63	415.03	448.18	437.61	378.36	367.25	411.72	468.97	718.31	1232.58
	NDTI (0 sampai 1)	146.31	281.97	39.71	14.11	4.46	3.27	45.58	44.33	85.13	71.93
Sopura	NDVI (-1 sampai 0.25)	69.12	67.43	70.91	71.73	70.73	73.69	78.81	84.26	90.14	88.39
	NDTI (0 sampai 1)	8.05	15.34	20.92	7.77	6.3	6.52	7.67	25.61	27.49	34.53
Tabelawa	NDVI (-1 sampai 0.25)	39.64	36.56	36.23	36.07	34.72	37.3	48.08	52.97	56.26	53.4
	NDTI (0 sampai 1)	7.92	12.33	28.72	7.74	4.47	4.53	14.94	38.36	35.75	38.05
Totobo	NDVI (-1 sampai 0.25)	79.13	77.48	91.96	109.56	97.2	96.16	101.93	99.68	102.77	91.43
	NDTI (0 sampai 1)	11.93	13.81	9.14	6.97	4.54	2.15	38.17	90.36	61.38	87.07

Source: Data Analysis (2026)

In general, the analysis results indicate a trend of increasing land clearing for nickel mining in most watersheds, particularly in the Mekongga, Lombato, Okooko, and Konoro watersheds. The Mekongga watershed, for example, showed a significant increase in areas with low NDVI values, from 466.94 ha in 2016 to 863.97 ha in 2025. A similar pattern was also identified in the Lombato and Okooko watersheds, which experienced a consistent increase in land clearing until 2025.

This increase in land clearing was accompanied by a trend of increasing coastal sedimentation, as reflected in the NDTI values in the watershed estuary zone. The Okooko and Konoro watersheds showed relatively high sedimentation areas during the 2024–2025 period, with NDTI values reaching 71.93 ha and 159.77 ha, respectively. This indicates that watersheds with extensive mining concessions tend to contribute to increased sediment supply to coastal areas. Conversely, watersheds with relatively small and stable land concessions, such as the Lepe and Tabélawa watersheds, exhibit lower and fluctuating coastal sedimentation rates. This demonstrates the important role of vegetation cover in suppressing surface runoff and reducing sediment transport to estuaries.

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Overall, the relationship between areas with low NDVI values and sedimentation rates based on the NDTI reinforces the indication that land cover changes due to nickel mining activities influence watershed hydrological responses and sedimentation processes in coastal areas. This finding aligns with the concept that increased land clearance and reduced vegetation cover increase surface runoff and soil erosion, which in turn increases the sediment load transported to downstream and coastal areas.

Conclusion

Based on the analysis, nickel mining activities in Pomalaa District, Kolaka Regency, have been shown to significantly impact the hydrological response of the watershed and sedimentation processes in coastal areas. The open-pit mining system causes increased land clearing and decreased vegetation cover, as indicated by the dominance of low NDVI values (-1 to 0.25), thereby increasing surface runoff and the potential for erosion, especially in hilly areas in the upper reaches of the watershed. The eroded material is rapidly transported through short river networks that flow directly into the sea, thereby increasing the supply of sediment to coastal areas. This increased sedimentation is reflected in higher NDTI values at watershed estuaries with extensive mining land clearings, such as the Mekongga, Lombato, Okooko, and Konoro watersheds. These findings confirm the strong upstream-downstream relationship between land cover changes due to nickel mining, the hydrological response of the watershed, and the intensity of coastal sedimentation. Therefore, integrated, watershed-based management of the mining environment is necessary to maintain the sustainability of coastal ecosystems.

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