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Classification and Monitoring of Kahayan River Riparian Zone Settlement Expansion Utilizing Satellite Imagery to Prevent Environmental Damage

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Abstract

As the population residing along the Kahayan River increased, many tall trees were cut down. This rapid growth of settlements negatively impacted environmental quality and accelerated soil erosion. Human activities such as tree logging and mining further aggravated erosion along the riverbanks, increasing the risk of flooding and damaging ecosystems. Settlements on the riverbanks became vulnerable to flooding, especially during heavy rains, which could destroy buildings and cause significant financial losses. This study aims to understand the relationship between settlement development and forest loss in the riparian zone of the Kahayan River in Palangka Raya City. To achieve this goal, high-resolution imagery and Geographic Information System (GIS) were used in conjunction with periodic satellite image classification methods. The main findings of the study show a drastic landscape transformation. During the study period, settlement areas expanded exponentially by 412%, increasing from 47.44 hectares to 243.07 hectares. This trend inversely correlated with a significant 57% reduction in riparian forest cover, decreasing from 390.08 hectares to 166.66 hectares. These findings have dual implications. Institutionally, the data provide an urgent empirical basis for local governments to formulate stricter and more effective spatial planning policies. Theoretically, this study strengthens understanding of the cause-and-effect relationship between urbanization processes and the degradation of sensitive riparian ecosystems. This quantitative evidence underscores the need to integrate urban planning and environmental conservation to achieve sustainable development.

1. Introduction

The urbanization of river basins has been a topic of discussion in the fields of spatial planning and the environment over the past three years (Sejati et al., 2025; Sejati et al., 2024). Several problems arise when areas that should be protected are instead used for expansion of built-up areas as a result of uncontrolled housing development (Buchori & Tanjung, 2014). This is an important issue worldwide because watersheds should be protected as part of their protective function and should not be used for built-up land.

One of the fastest growing areas and a center of global attention is Kalimantan (Borneo). The issues of deforestation and land conversion around rivers are major problems and threaten sustainability in Kalimantan. Furthermore, this condition is also experienced by Palangka Raya City, the capital of Central Kalimantan Province, which has the Kahayan River, one of the longest rivers in Indonesia (600 km in length, 500 meters in width, and 7 meters in depth). For the Dayak Ngaju ethnic group, the largest tribe in Central Kalimantan, this river is the center of life, upon which they rely for various needs, including logging, forest product collection, fisheries, and traditional agriculture (Sutrisno et al., 2019; Suwito et al., 2020; Wainarisi & Tumbol, 2022). Historically, the riverbanks have functioned as focal points for human habitation, with villages situated along its edges (Heriyanto et al., 2022; Siburian et al., 2025). The Kahayan River plays a crucial role in the ecological functioning of Palangka Raya City, yet rapid settlement expansion has caused significant environmental alterations and degradation (Segah et al., 2023). The dynamic urban growth and organic spread of settlements have triggered a shift in settlement patterns away from the river, a transition that contradicts the river's original role as a guiding element for the Dayak Ngaju community (Usop et al., 2022).

Previous studies on environmental degradation, particularly around rivers, have focused only on the impact of activities around rivers on land quality. Such as this environmental degradation is manifested in the silting of the river, erosion that increases water turbidity, and accumulation of waste (Dirun et al., 2021; Marlina & Novrianti, 2018). Elevated erosion negatively impacts fish populations and raises the flood risk in surrounding settlements (Srivastava & Tripathi, 2022). The problems of plastic waste and inadequate sanitation further exacerbate the situation, with domestic waste often being directly discharged into the river (Jovanović, 2017; Martani et al., 2022; Riani & Cordova, 2024). Moreover, environmental damage is aggravated by the loss of trees that function as the land cover due to settlement expansion (Cantera et al., 2023). Another interesting study also focused on indigenous customary forest ownership has been converted for palm oil plantations and mining activities, which not only pollute river flows but also shift community livelihoods from the primary sector (forestry) to secondary and tertiary sectors (Bose-O'Reilly et al., 2016; Fikri et al., 2023; Jayanti et al., 2025; Usop et al., 2022). The land cover changes caused by human activities necessitate in-depth analysis to facilitate sustainable land use planning and ecosystem conservation, and the analysis of riparian zone changes can be effectively conducted using satellite imaging technology (Chapa et al., 2019). Previous research has not focused on time series monitoring and measures for environmental policy-making in areas surrounding rivers.

Given this gap, this study offers a method for rapid assessment as a first step in policy-making for spatial utilization control in riverine areas. Given the urgency of this issue, this study aims to present the results of satellite imagery processed using Google Earth Pro from 2014 to 2023 for an integrated monitoring system for riverine areas. This research complements previous studies, particularly in terms of contributing knowledge on monitoring areas around rivers, which not only focuses on existing conditions but is also capable of predicting future conditions.

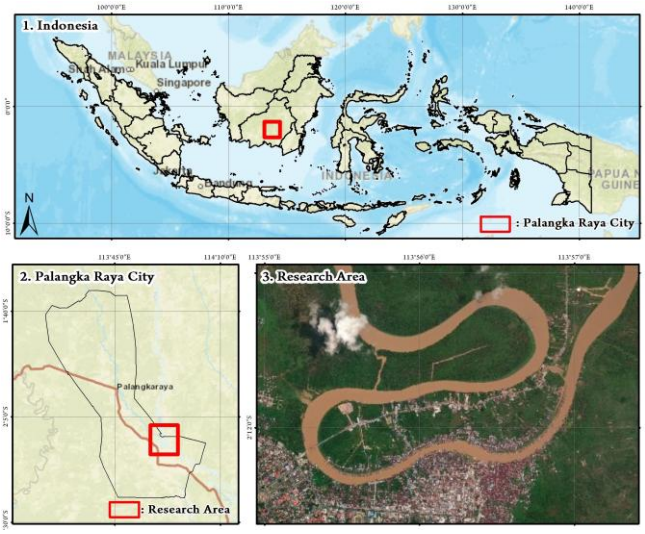
2. Data and Methods

2.1. Study Area

The designated geographical region is commonly referred to as Pahandut Seberang. Situated in the city of Palangka Raya in the province of Central Kalimantan, Indonesia. The research area encompasses the riparian area of the Kahayan River, with a total area of 702.57 hectares (Figure 1). Pahandut Seberang is situated on the opposite bank of the river from the central area of Palangka Raya, with distinct geographical and infrastructural characteristics. Both locations can be accessed either by crossing a bridge or by traveling on water. The topographical features exert a significant influence on people's preference for river transportation, particularly motorized boats, as a means of travel and accessing different destinations. This motorized boat serves as a dependable means of transportation for accessing the forests surrounding the Kahayan River in order to gather forest products. Additionally, it is occasionally used to repair peat infrastructure in order to prevent forest fires (Perkasa et al., 2024).

The number of houses in this region correlates with the expansion of Palangka Raya city. Land use can be altered as a result of population growth and the demand for housing. This can involve deforestation and altering the ecological dynamics of the region, such as watershed hydrology and increased flood vulnerability (Pumo et al., 2017; Segah et al., 2023). The income and livelihood of the Pahandut Seberang community are dependent on fishing, agriculture, small-scale enterprises, and offering transportation services to community members via motorboats. Such community enterprises typically exert an influence on the surrounding environment, manifesting in activities such as pollution or alteration of land use (Dirun et al., 2021).

The process of urbanization in Pahandut Seberang poses a significant threat to the environment, as it leads to the destruction of natural habitats, exacerbates pollution, and disrupts the functioning of the local ecosystem (Pumo et al., 2017). In order to comprehend and resolve this issue, it is crucial to undertake study on the repercussions of an increased population residing in the vicinity. Pahandut Seberang is undergoing rapid transformation as the city of Palangka Raya progresses (Wijaya & Herlambang, 2022). Changes in land usage, environmental implications, and social and economic expansion present both challenges and opportunities.



Source: Authors, 2024

Figure 1. Research Area Located in the Riparian Area of Pahandut Village, Adjacent to the Seberang Kahayan River in Palangka Raya

2.2. Research Design

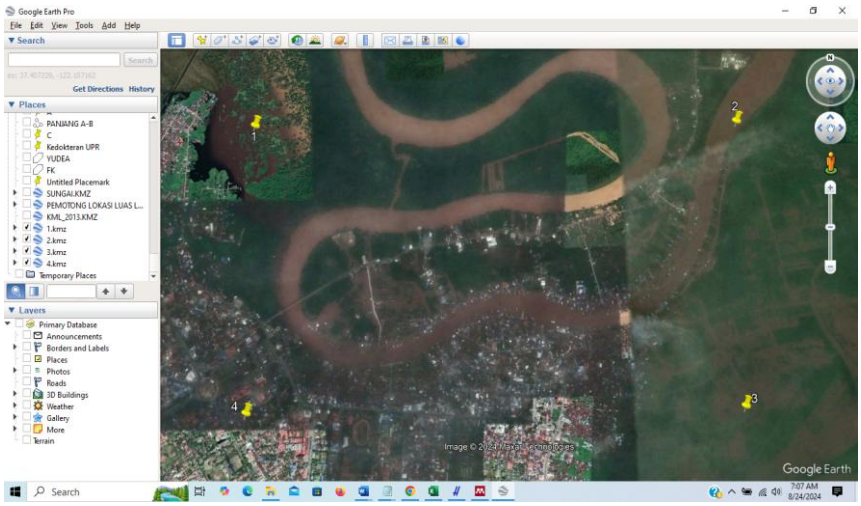
A quantitative descriptive technique to studying land cover change involves collecting and analyzing numerical data to demonstrate how land usage or cover varies over time. This quantitative descriptive methodology facilitates the identification of patterns and trends in alterations in land cover, enabling the classification and monitoring of the spread of human settlements in the riparian zone of the Kahayan River (Donatien et al., 2024). This approach also facilitates the organization and coordination of tasks more effectively. The research concept will utilize satellite photos captured at various time intervals to gather data on land cover (Mengist et al., 2020). This utilization of multi-temporal data represents a fundamental approach in river environment studies, both for tracking physical changes such as riverbank erosion (Khan et al., 2017) and for quantifying changes in land use functions (Vaggela et al., 2022).

Field data obtain their information from surveys or records collected directly in the field. Image processing methods are employed in land cover classification to categorize satellite imagery into specific land cover types, such as settlement expansion. Specifically, the supervised classification method is a reliable technique for this purpose (Vaggela et al., 2022). Images from different periods are compared using temporal analysis to identify changes in land cover (Setiabudi & Kusumaningrum, 2021). This method enables the observation of changes over time and the identification of emerging trends.

Descriptive statistical data analysis is employed to draw definitive and precise conclusions on land cover. This encompasses understanding the dimensions of each land cover category, the rate at which it undergoes change over time, and its spatial distribution (Burrough, 2001). Mapping and visualization involve the creation of thematic maps or other visual representations that illustrate the temporal and spatial changes in land cover. The graphic displays a transition from one sort of cover to another. Data interpretation offers a comprehensive understanding of the mechanisms and reasons behind alterations in land cover. This include factors that induce alteration, such as the proliferation of human settlements, deforestation, or modifications in the availability of open land (Nitze et al., 2015).

2.2 Data Analysis

Data analysis employs periodic satellite image classification to detect changes in land cover by delineating the polygon area of interest (AOI) based on the boundaries of the target region, specifically the riparian zone of the Kahayan Pahandut River in Palangka Raya City (Figure 2). Import polygon data into Google Earth Pro by uploading a file in either KML or KMZ format. Once the AOI polygon has been appropriately aligned with the image, proceed with executing the download command. The subsequent step involves georeferencing the image by assigning geographic coordinates, enabling accurate placement of the image on a map or other GIS data within the software.



Source: Google, 2024

Figure 2. The Process of Creating an AOI and Downloading Picture Data in Google Earth Pro is Captured in Layers

Four placemarks are strategically positioned at the corners of the viewer to serve as geographic reference points. These placemarks are then recorded in KML format. Software is utilized for image preprocessing and for land cover analysis. The conversion process involves transforming each JPG file into a GeoTIFF raster format using KML points as Ground Control Points (GCP) for georeferencing. Ultimately, the regions of interest are trimmed to their corresponding limits. Exporting photos from Google Earth Pro at the eye level consistently yields a pixel resolution of 0.2 meters. These values correspond to the necessity of differentiating specific urban characteristics, such as small areas of greenery or cars. Lowering the eye height can result in equivalent or improved pixel quality (Tonyalouglu et al., 2021).

Perform image-based land cover classification using Supervised Classification, which requires manual determination of sample classes, to identify and categorize different types of land cover. AOI is categorized into five primary land cover classes, namely Land, Shrubs, Settlement, Forest, and Water Body (Padmini et al., 2023). OSM files contain exported representations of roads and rivers from OpenStreetMap (Jaroszewicz et al., 2023). The data is transformed into a shapefile. The road's width is established by converting the lines into polygons.

3. Result and Discussion

Google Earth Pro allows for the capture of image data in the years 2014, 2016, 2018, 2020, and 2023. This satellite image has a great level of detail, since each pixel in the image can accurately represent a small section of the Earth's surface, with a resolution of approximately 30 cm per pixel (Wang et al., 2023). This feature enables users to perceive relatively small entities, such as trees, vehicles, or buildings. Google Earth Pro sources its satellite images from multiple commercial and public vendors, including DigitalGlobe (formerly Maxar Technologies) and CNES/Airbus. Satellite photos are often updated; however, the updates are not synchronized globally. locations of higher popularity or significance may undergo more frequent updates compared to less important locations (Warnasuriya et al., 2020).

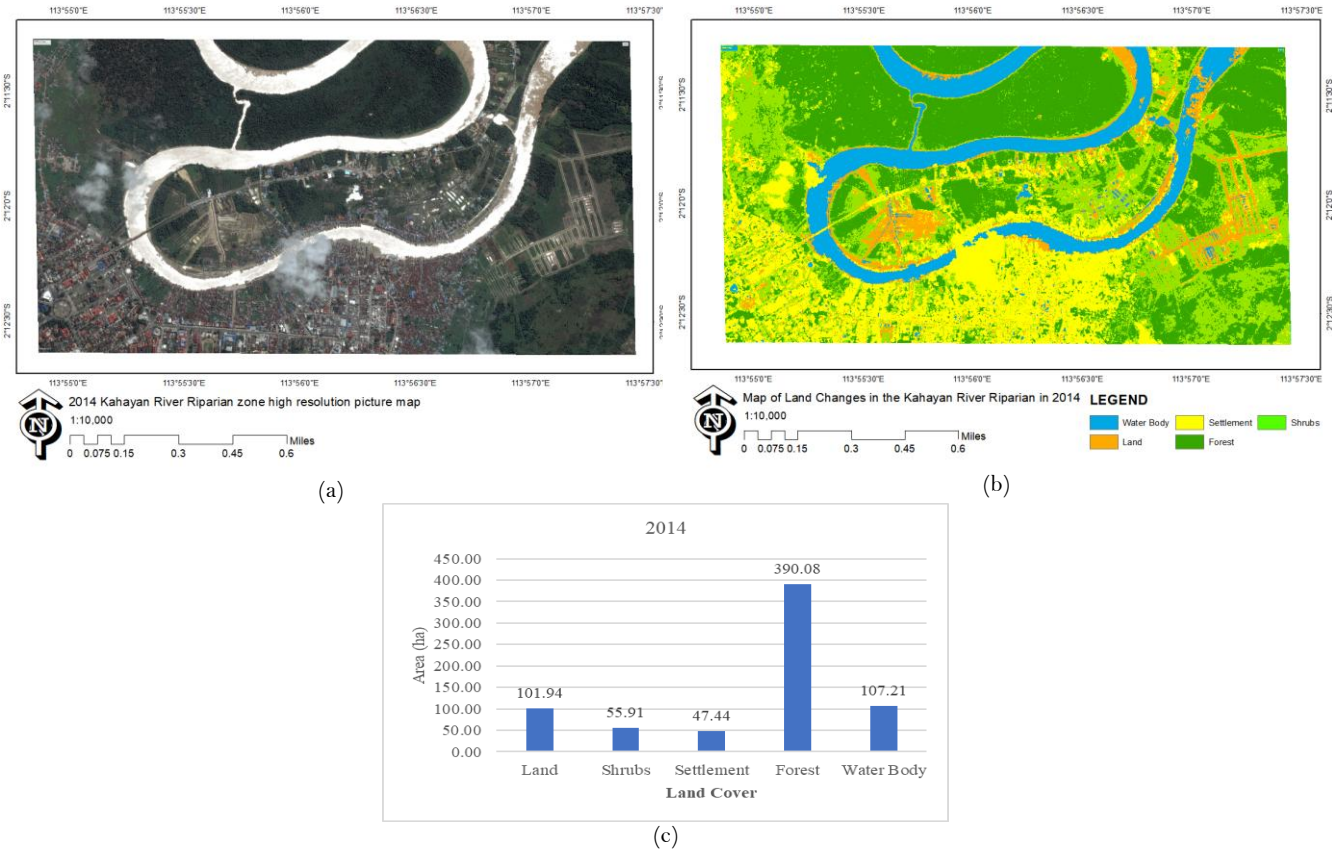


Figure 3. Assessment of Alterations in the Land Cover of the Riparian Zone along the Kahayan River in the year 2014. (a) Photograph taken in 2014. (b) Map Depicting the Distribution of Land Cover in the year 2014. (c) The Land Cover Area in 2014

The findings of the regular analysis of satellite images to detect alterations in the land surface of the study area in 2014 are displayed in Figure 3. The analysis was conducted in 2014 using periodic satellite image classification. The results showed that there were 101.94 hectares of land, 55.91 hectares of shrubs, 47.44 hectares of settlement, 390.08 hectares of forest, and 107.21 hectares of water bodies. This indicates that the region has notable hydrographic features (Nugraha et al., 2022). The presence of several water bodies might be indicative of the existence of various aquatic ecosystems, such as swamps or river deltas, which provide a habitat for a wide range of aquatic flora and fauna (de Rosari et al., 2020). The riparian forest surrounding the research site remains thick and expansive, serving a crucial function in preserving ecological equilibrium along waterways, fostering biodiversity, and offering essential ecosystem services for both humans and the environment (Jamaludin et al., 2020). The human population is relatively small and resides in uncomplicated conditions, relying heavily on rivers as a vital source of sustenance. The estimated population of Palangka Raya in 2014 was between 240,000 to 250,000 individuals (BPS Palangka Raya City, 2023).

The findings of the regular analysis of satellite images to detect alterations in land cover at the study site in 2016 are displayed in Figure 4. The analysis was conducted in 2016 using periodic satellite image categorization. The results showed that the land area was 136.97 hectares, shrubs covered an area of 28.37 hectares, settlements occupied 61.10 hectares, forests spanned 365.63 hectares, and there was a water body covering 110.50 hectares. The projected population of Palangka Raya in 2016 ranged from approximately 265,000 to 275,000 individuals. The growth of the city is fueled by urbanization, migration from rural areas, and advancements in the economic and educational sectors, which consistently draw in new citizens (BPS Palangka Raya City, 2023). In 2016, Palangka Raya underwent ongoing infrastructure development, encompassing enhancements to its road network, bridges, and many public amenities. The construction of this infrastructure is crucial for facilitating urban expansion, enhancing mobility, and enhancing the citizens' standard of living. The forest's state is deteriorating as towns continue to expand.

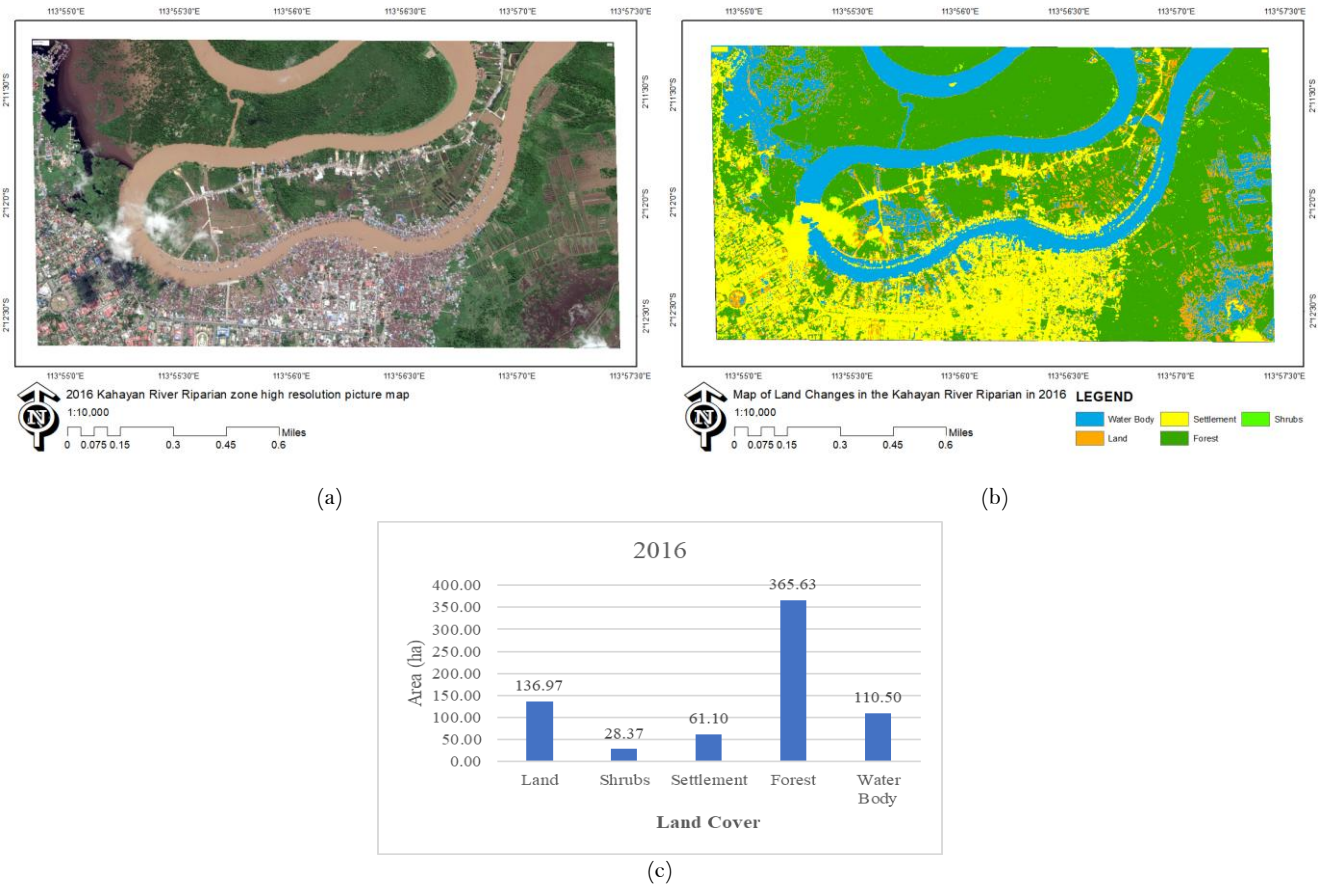


Figure 4. Assessment of Alterations in the Land Cover of the Riparian Zone along the Kahayan River in the year 2016. (a) Photograph taken in 2016. (b) Map Depicting the Distribution of Land Cover in the year 2016. (c) The land Cover Area in 2016

The findings of the regular analysis of satellite images to detect alterations in land cover at the study site in 2016 are displayed in Figure 4. The analysis was conducted in 2016 using periodic satellite image categorization. The results showed that the land area was 136.97 hectares, shrubs covered an area of 28.37 hectares, settlements occupied 61.10 hectares, forests spanned 365.63 hectares, and there was a water body covering 110.50 hectares. The projected population of Palangka Raya in 2016 ranged from approximately 265,000 to 275,000 individuals.

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2016, Palangka Raya underwent ongoing infrastructure development, encompassing enhancements to its road network, bridges, and many public amenities. The construction of this infrastructure is crucial for facilitating urban expansion, enhancing mobility, and enhancing the citizens' standard of living. The forest's state is deteriorating as towns continue to expand.

The findings of the regular analysis of satellite images to detect alterations in the land's surface in the specified research area over the year 2018 are displayed in Figure 5. The analysis was conducted in 2016 using periodic satellite image classification. The results showed that there were 106.86 hectares of land, 33.52 hectares of shrubs, 191.92 hectares of settlement, 273.70 hectares of forest, and 96.57 hectares of water bodies. The estimated population of Palangka Raya in 2018 exceeds 260,000 individuals. This rise is consistent with the pattern of urbanization and migration from rural regions to urban areas, propelled by economic prospects and improved amenities in Palangka Raya (BPS Palangka Raya City, 2023).

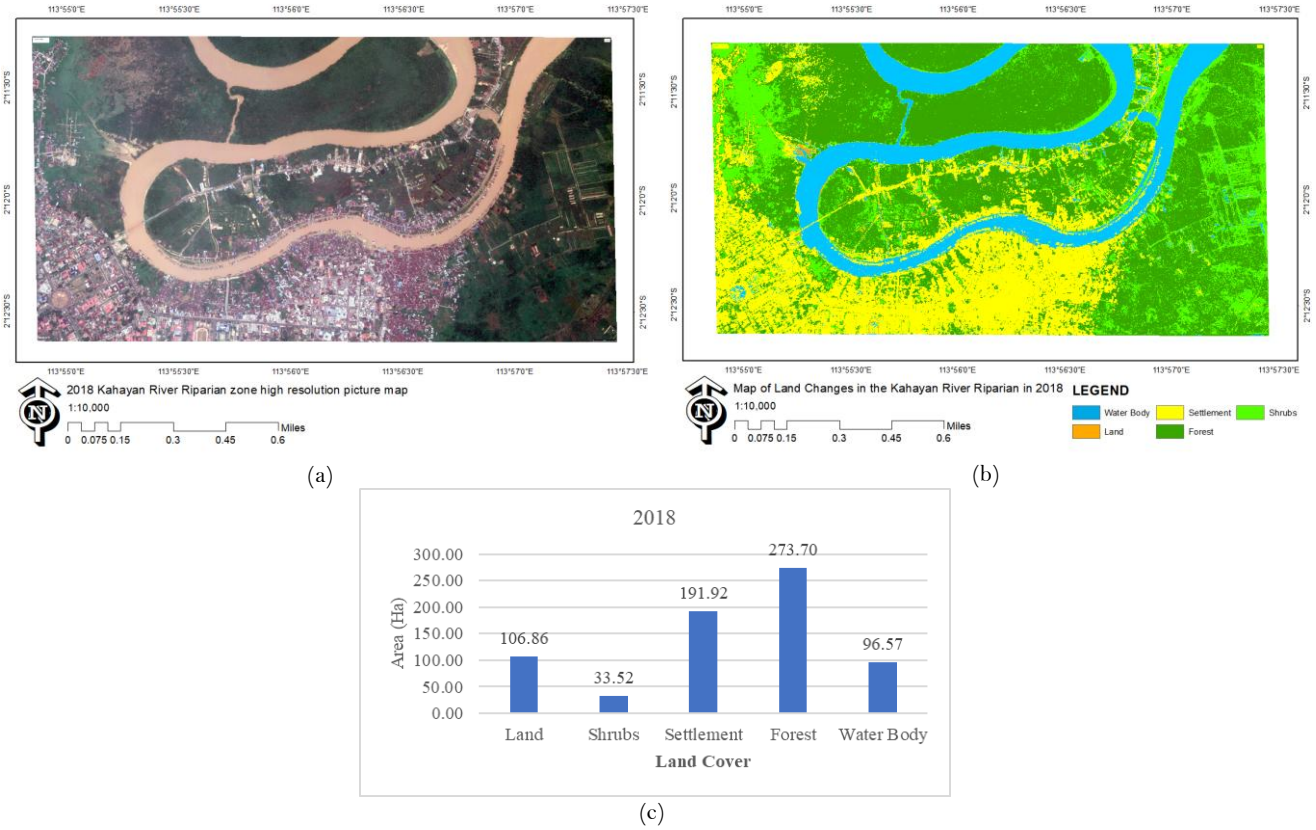


Figure 5. Assessment of Alterations in the Land Cover of the Riparian Zone Along the Kahayan River in the year 2018. (a) Photograph Taken in 2018. (b) Map Depicting the Distribution of Land Cover in the year 2018. (c) The Land Cover Area in 2018

An intriguing matter in 2018 revolved on the preliminary deliberation on the feasibility of relocating the Indonesian capital from Jakarta to Kalimantan. Palangka Raya was frequently cited as a prospective contender because of its advantageous position in the heart of Indonesia. However, no definitive decision had been reached by the end of that year (Hantoro, 2018). Palangka Raya is currently undergoing population growth and urbanization, as a significant number of immigrants are choosing to establish residence in the city. There is a noticeable upward trajectory in land cover analysis, which is driving the need for housing, infrastructure, and other public services. Urbanization leads to the spread of settlements into suburban regions, necessitating the provision of essential services and infrastructure.

The outcomes of the regular analysis of satellite images to detect alterations in the land cover of the study area in 2020 are displayed in Figure 6. The analysis was conducted in 2020 using periodic satellite image classification. The results showed that there were 120.41 hectares of land, 67.31 hectares of shrubs, 223.88 hectares of settlement, 190.20 hectares of forest, and 100.76 hectares of water bodies. The projected population of Palangka Raya in 2020 is expected to range between 290,000 and 300,000 individuals. The city center and well-established residential areas, such as Pahandut and Jekan Raya subdistricts, have the highest population density. These places serve as hubs for commercial, governmental, and educational activities (BPS Palangka Raya City, 2023).

The unemployment rate is rising due to companies downsizing or shutting down. This leads to an escalation in poverty rates, necessitating the government to offer social support to impacted residents. The proliferation of settlements in riverfront locations has persisted during the Covid 19 pandemic. In general, the number of communities along the banks of the Kahayan River has grown due to their practicality and adherence to the economic, cultural, and environmental requirements of the local population. Rivers serve as vital sources of resources and also hold significant significance in the social and cultural fabric of communities (Selly et al., 2021).

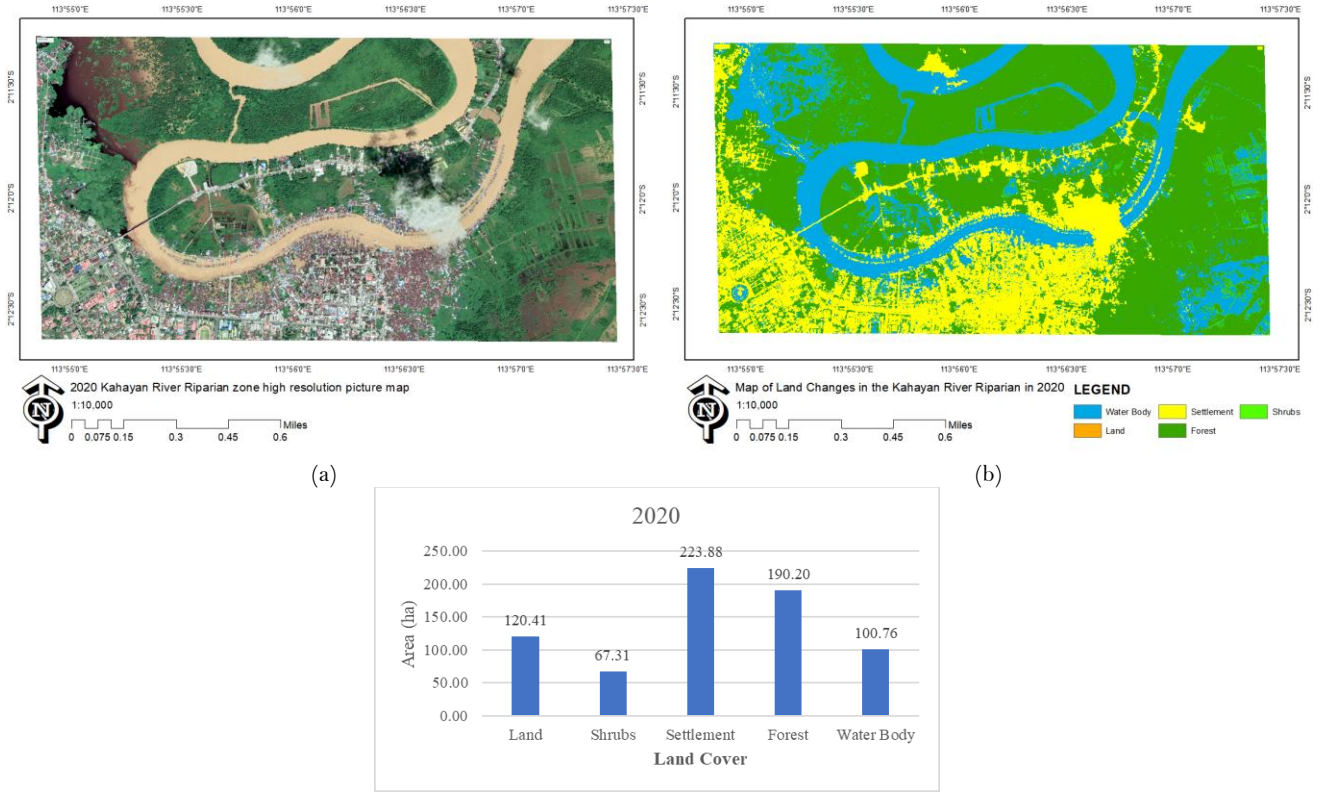


Figure 6. Assessment of Alterations in the Land Cover of the Riparian Zone along the Kahayan River in the year 2020. (a) Photograph taken in 2020. (b) Map Depicting the Distribution of Land Cover in the year 2020. (c) The Land Cover Area in 2020

The outcomes of the periodic analysis of satellite images to detect alterations in land cover at the specified research site in 2023 are displayed in Figure 7. The analysis was conducted in 2023 using periodic satellite image categorization. The findings of the analysis showed that the land area was 116.04 hectares, shrubs covered an area of 58.24 hectares, settlements occupied 243.07 hectares, forests spanned 166.66 hectares, and there was a water body measuring 118.56 hectares. The population in 2023 fluctuated between 310,000 and 320,000 individuals. The population growth demonstrates an ongoing pattern of urbanization, resulting from both

internal migration and natural increase through births. These locations serve as the focal points for commercial, governmental, and educational activities (BPS Palangka Raya City, 2023).

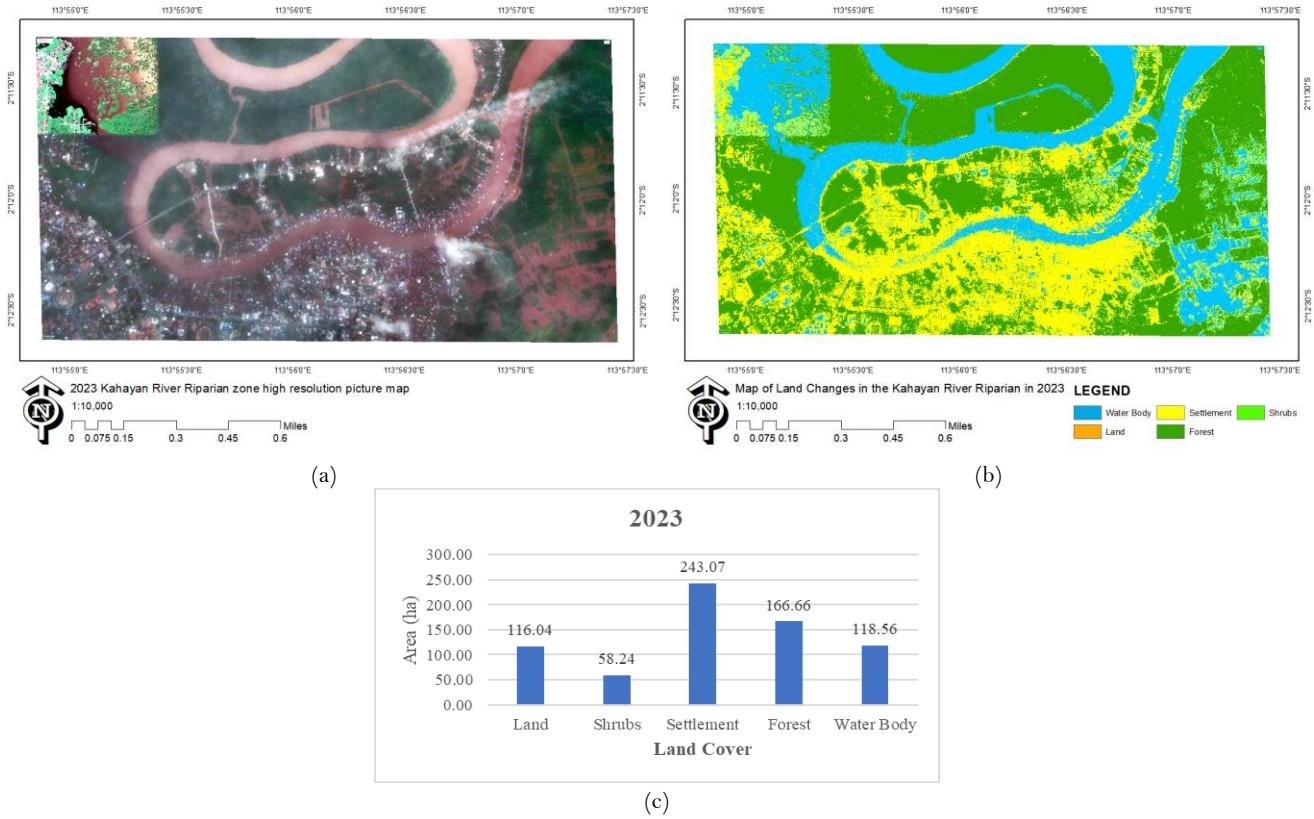


Figure 7. Assessment of Alterations in the Land Cover of the Riparian Zone Along the Kahayan River in the year 2023. (a) Photograph taken in 2023. (b) Map Depicting the Distribution of Land Cover in the year 2023. (c) The Land Cover Area in 2023

In Palangka Raya, the year 2023 is characterized by a multitude of transformations and obstacles, primarily centered around recuperating from the repercussions of the epidemic and advancing infrastructural development. Observations indicate that the rate of human habitation has surpassed the extent of forest cover in the riparian zone of the Kahayan River in Pahandut Seberang Palangka Raya City.

Monitoring the spread of settlements also has a significant impact on the occurrence of environmental damage. Monitoring is a crucial procedure for gathering precise data on environmental conditions and the effects of damage. Early detection of environmental issues is crucial for effective monitoring (Budiyanti et al., 2020). Various sites within the riparian zone of the Kahayan River are utilized as monitoring sites for studying waste accumulation, erosion along the river banks, and logging activities. These monitoring sites are depicted in Figure 8. Surveillance of plastic garbage in the Kahayan River reveals a rise in the buildup of plastic debris during the rainy season, as it is transported by the river's currents. This data can motivate local governments to enhance waste management programs in rivers located upstream and raise public consciousness regarding the consequences of plastic garbage on ecosystems in river basins. An effective solution in this context is the implementation of a waste management system that is based on the local community. Plastic can be transformed into recycled plastic ore through the process of recycling (Samadikun et al., 2020).

To effectively address erosion on the banks of the Kahayan River, a cost-effective and efficient method involves rehabilitating the area with riparian vegetation. This entails planting trees and plants that are well-suited to the river bank environment, hence enhancing the stability and strength of the river bank. The plant's roots serve to anchor the soil and inhibit erosion (Lafage et al., 2019). An effective strategy for the long term is to provide education to individuals regarding the significance of safeguarding river banks and the detrimental

effects of human actions, such as deforestation and unauthorized construction, which can intensify erosion. Engage local people in reforestation and riparian vegetation restoration initiatives to enhance communal consciousness and accountability (Oprasmani et al., 2020).

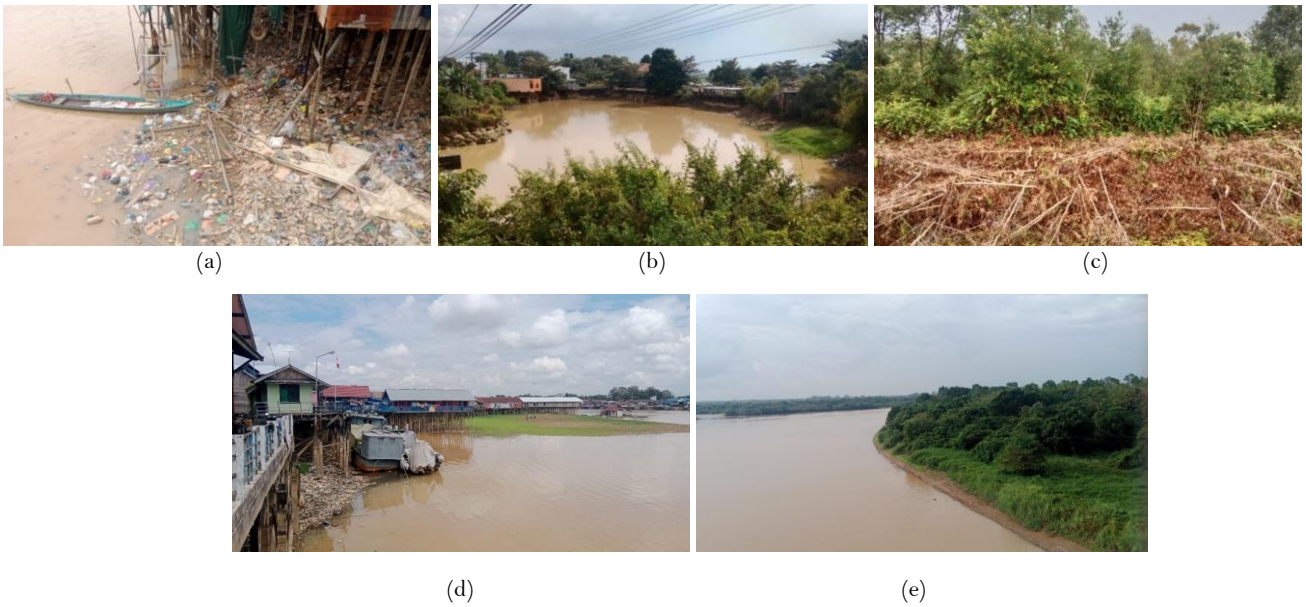


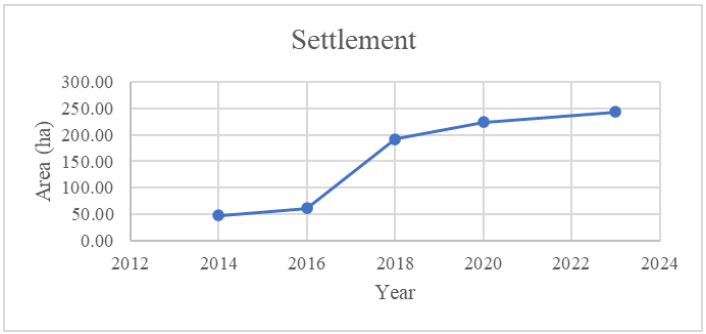
Figure 8. The documentation of monitoring the spread of settlements also has a significant influence on the extent of environmental harm in 2024. (a) The buildup of plastic debris in the riparian zone of the Kahayan River. (b) The Kahayan tributary was closed because of erosion and the construction of a damaged bridge. (c) Harvesting timber for the purpose of constructing materials. (d) Increase in the size of human settlements in the riparian zone of the Kahayan River. (e) Riparian zones that continue to retain their sustainability

Settlement expansion can take place either gradually or swiftly, depending on the rate of population growth and the policies implemented for development. In certain regions, the rate of development can surpass the environment's ability to sustain it. The increase of settlements and the loss of trees in the riparian zone of the Kahayan River provide a serious challenge to sustainable development and environmental conservation. Expansion of settlements frequently results in the direct alteration of existing forests and vegetation, resulting in the loss of trees and degradation of ecosystems. The comparison is illustrated in Figure 9 below.

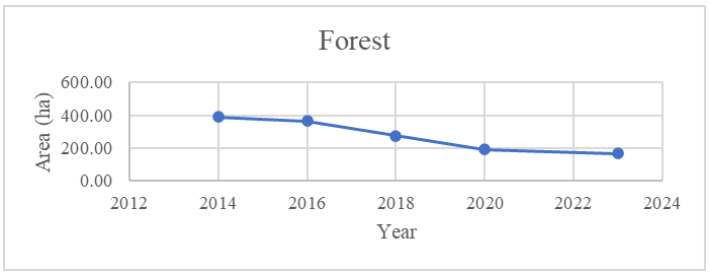
Deforestation also leads to the depletion of vital resources for communities, including firewood, fruit, and traditional remedies. In addition, communities reliant on trees for their sustenance may face the loss of their means of living (Meilani et al., 2021). Trees have a crucial role in preserving soil moisture and mitigating erosion. Deforestation leads to soil deterioration, diminished fertility, and heightened susceptibility to landslides. Robust zoning restrictions, stringent building standards, and effective urban planning are necessary to safeguard the environment from potential harm caused by residential expansion (Putraditama et al., 2019).

Multi-temporal analysis of land cover in the riparian zone of the Kahayan River from 2014 to 2023 reveals a significant and rapid landscape transformation. The main findings of this study confirm a reciprocal relationship between the expansion of settlements and the reduction of riparian forests, driven by urbanization and population growth. Quantitative results from satellite image classification indicate a strikingly contrasting trend between the two primary land cover classes. Over the nine-year period (2014–2023), settlement areas increased exponentially from 47.44 ha to 243.07 ha, representing a surge of 412%. Conversely, forest cover in the same zone experienced a drastic decline from 390.08 ha to only 166.66 ha, amounting to a 57% loss of the total forest area in 2014. These opposing trends are clearly visualized in Figure 9, which illustrates how the settlement growth curve rises consistently while the forest cover curve sharply declines. These findings directly address the research gap identified in the Introduction by providing previously unavailable multi-temporal

quantitative data on the rate and scale of changes within this specific study area. This rate of change, therefore, indicates intense development pressure on the riparian ecosystem.



(a)



(b)

Figure 9. An Analysis of the Expansion of Human Settlements and the Loss of Forested Areas (a) The Growth of Settlements from 2014 to 2023. (b) The Extent of Deforestation between 2014 and 2023

This massive expansion of settlements strongly correlates with the population growth of Palangka Raya City, which increased from approximately 240,000 inhabitants in 2014 to more than 310,000 in 2023. This growth has been driven by urbanization and migration, accelerated by infrastructure development. The observed pattern of settlement expansion is organic in nature and tends to follow accessibility along the riverbanks—a pattern consistent with studies on slum settlements in other river basins, that also highlight unplanned urban growth.

The loss of more than half of the riparian forest cover within a short period has serious ecological implications, as documented in Figure 8. This degradation is no longer a mere threat but an observable reality in the field, manifested in the accumulation of plastic waste, active riverbank erosion, and tree felling for construction materials. The loss of vegetation directly reduces the function of the riparian zone as a buffer zone, which should stabilize the soil and prevent erosion. Consequently, this has led to increased turbidity and sedimentation—phenomena that have also been reported in previous studies of the Kahayan River and other river basins. Furthermore, these findings are consistent with the study by Cantera et al. (2023), which directly links deforestation to functional changes in river ecosystems, including the decline of fish populations. Accordingly, the quantitative data from this research provide strong evidence that each hectare of riparian forest converted into settlement areas contributes directly to a broader chain of environmental degradation—ranging from erosion to the loss of biodiversity.

Therefore, firm and sustainable zoning policies and urban planning are needed to manage settlement growth in ways that do not harm the environment. However, implementing such policies must take into account the complexity of local ecosystems. Studies on policy interventions in riparian zones (Majumdar & Avishek, 2025) indicate that conventional approaches using fixed-width buffer zones often fail to address the complex interactions between buffer effectiveness and site-specific characteristics. In contrast, context-sensitive adaptive frameworks—where the minimum buffer width is adjusted based on ecological objectives (for example, 10–30 m

for erosion control and 30–100 m for nutrient retention) and local biophysical conditions—have proven more effective.

This approach enables the formulation of evidence-based policies that balance ecological protection with socio-economic considerations, while linking local environmental management to global Sustainable Development Goals (SDGs). Such policies must be accompanied by education and active community participation in greening and riparian vegetation restoration programs to enhance awareness and collective responsibility. The integration of social and environmental aspects into development planning is expected to create a balance between economic growth and natural resource conservation, thereby supporting ecosystem sustainability and improving the quality of life for the people of Palangka Raya.

4. Conclusion

This study confirms the occurrence of massive land cover changes in the riparian zone of the Kahayan River during the 2014–2023 period. The novelty of these findings lies in the quantitative evidence demonstrating a 412% expansion of settlements, which contrasts sharply with a 57% reduction in riparian forest cover. These findings directly address the previously identified research gap concerning the availability of multi-temporal data capable of measuring the rate and scale of land-use change within the study area. The implications of these findings are highly significant for both institutional development and theoretical advancement. Institutionally, the quantitative data provide a strong foundation for local governments to formulate sustainable land-use planning and more assertive spatial policies. Theoretically, this study reinforces the understanding of the causal relationship between urbanization processes and environmental degradation, particularly within the sensitive riparian ecosystem. Based on these findings, two main recommendations are proposed for future research. First, spatial policy scenario modeling should be conducted to predict its effectiveness in curbing the rate of deforestation. Second, a more in-depth analysis is needed to explore the socio-economic factors that drive communities to settle within river buffer zones, so that policy interventions can be designed to be more practical and contextually relevant

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