Realtime and Spatial Data Analysis-based Monitoring System for Proboscis Monkey Habitat Health to Enhance Conservation Area Management Effectiveness

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(Received: July 27, 2024; Revised: July 30, 2024; Accepted: August 18, 2024; Available online: October 19, 2024)

Abstract

The conservation of proboscis monkeys (Nasalis larvatus), an endemic primate species of Borneo, faces significant threats due to habitat degradation and declining populations. This study aims to develop a real-time and spatial data analysis-based monitoring system to improve the management of conservation areas for the species' natural habitats. Conducted in the wetland ecosystems of Curiak Island, South Kalimantan, the research integrates remote sensing, Geographic Information Systems (GIS), and Internet of Things (IoT) technologies to monitor key environmental parameters such as vegetation health, land surface temperature (LST), and others. Indices like the Normalized Difference Vegetation Index (NDVI), Vegetation Health Index (VHI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI), and Environmental Critical Index (ECI) are utilized to assess habitat conditions. Initial results showed poor vegetation health, with an NDVI of 0.6085, high LST of 20.41°C, and considerable environmental stress, reflected by an ECI of 74. Restoration efforts, however, improved conditions, with the NDVI rising to 0.7288, LST decreasing to 20.75°C, and the ECI lowering to 53 in the restoration area, signaling recovery. Though the ECI still suggests moderate environmental stress, the trend is positive. IoT sensors provided continuous real-time data, including CO levels at 0.2 PPM, CO2 at 34,045 PPM, O2 at 20.4% Vol, temperatures ranging from 33.155°C to 33.185°C, humidity between 67.45% and 67.65%, and pH at 6.8. Data on dissolved oxygen, total dissolved solids (TDS), and turbidity were also collected, providing dynamic insights into environmental conditions. The integration of community-based approaches ensures sustainable conservation efforts through local participation. This comprehensive monitoring system supports both proboscis monkey conservation and broader ecological objectives like biodiversity preservation, climate change mitigation, and ecosystem service provision, emphasizing adaptive management in conservation strategies.

Keywords: Proboscis Monkey, LST, NDVI, VHI, ECI, Realtime Data

1. Introduction

The conservation of proboscis monkeys (Nasalis larvatus), an endemic primate species to the island of Borneo, has become a critical issue due to their declining population and the degradation of their natural habitat. As an arboreal species, proboscis monkeys inhabit various wetland habitats such as gelam swamp ecosystems, peat swamps, and mangrove forests along riverbanks [1], [2]. These ecosystems provide essential resources and conditions necessary for the survival of proboscis monkeys and other wildlife. Protecting these habitats is crucial for maintaining the ecological balance and biodiversity of the region. Wetland ecosystems, particularly mangrove forests, play a significant role in protecting the land from erosion, supporting fisheries, and maintaining the genetic diversity of flora and fauna [3]. Proboscis monkeys contribute to the health of these ecosystems by consuming leaves and shoots, promoting plant growth and forest regeneration [4]. For example, studies have shown that their feeding habits help in dispersing seeds and creating gaps in the forest canopy, which facilitate the growth of new plants [5], [6]. However, these habitats are

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DOI: https://doi.org/10.47738/jads.v5i4.334

under threat from human activities such as land conversion for agriculture, aquaculture, mining, and urban development. These activities lead to habitat fragmentation, reducing the availability of resources and suitable living conditions for proboscis monkeys [2].

The Environmental Critical Index (ECI) is a valuable tool for assessing the health and vulnerability of an ecosystem. ECI integrates data on land surface temperature and vegetation cover to identify areas at risk of environmental degradation [7]. It takes into account specific environmental parameters such as soil moisture, vegetation health, and thermal conditions. For instance, a study on ECI in Kendari highlighted how changes in land use from vegetated to developed areas can significantly increase surface temperatures and decrease vegetation density, leading to higher environmental criticality [8]. These insights can inform targeted conservation efforts in proboscis monkey habitats to mitigate similar risks. Similarly, the Vegetation Health Index (VHI) [9] is used to monitor the health of vegetation by assessing moisture and thermal conditions. VHI combines the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) to provide a comprehensive picture of vegetation stress, which can result from factors like drought, disease, or human activities [10], [11]. Applying VHI to monitor wetland habitats can help detect early signs of stress in vegetation, enabling proactive conservation measures to protect these critical ecosystems [12].

The proboscis monkey population has declined dramatically over the past decades, with the International Union for Conservation and Natural Resources (IUCN) categorizing them as endangered [6]. Human-induced habitat destruction, along with low reproductive rates and hunting pressures, exacerbates the decline. Proboscis monkeys typically reach sexual maturity at around five years of age and usually give birth to a single offspring per pregnancy, making population recovery slow. As their natural habitats shrink, the monkeys face increased risks of starvation, disease, and stress, further hindering their ability to reproduce and survive [13]. To address these challenges, conservation efforts must prioritize the preservation and restoration of wetland habitats. Monitoring the health of proboscis monkeys and their habitats through realtime spatial data analysis can significantly enhance conservation strategies. By employing advanced technologies such as remote sensing and Geographic Information Systems (GIS) [14], [15], conservationists can track land-use changes, deforestation, and habitat degradation in real time, facilitating timely interventions to protect these critical areas [16]. This integrated approach ensures that the preservation efforts for proboscis monkeys extend beyond mere species conservation to encompass wider ecological benefits. By safeguarding their habitats, we also protect the myriad of ecosystem services that wetlands provide, such as carbon sequestration, water filtration, and flood mitigation. These services are crucial not only for biodiversity but also for mitigating the impacts of climate change and supporting human well-being [17].

Research indicates that the fragmentation of proboscis monkey populations into isolated sub-populations poses significant risks to their genetic diversity and overall survival [13]. These sub-populations, often separated by unsuitable or degraded habitats, face increased vulnerability to environmental changes and resource scarcity. Protecting large, contiguous wetland areas and establishing ecological corridors can mitigate these effects by providing stable environments conducive to larger, interconnected populations. This connectivity is essential for maintaining genetic flow and resilience against local extinctions [12], [17]. Furthermore, localized conservation strategies, such as the protection of uninhabited islands that serve as natural sanctuaries, have shown promise in providing safe havens for proboscis monkeys. These areas minimize human impact and maintain ecological integrity, allowing monkey populations to thrive. Additionally, responsible ecotourism management that involves local communities can generate financial resources to support ongoing conservation projects and raise public awareness about the importance of wetland ecosystems [18].

Incorporating community-based approaches into conservation plans ensures that local knowledge and traditional practices are integrated with scientific methods, enhancing the effectiveness and cultural relevance of conservation efforts [19]. For example, participatory ecotourism initiatives can create economic opportunities for local residents while fostering a sense of stewardship towards natural resources. This symbiotic relationship between conservation and community well-being is essential for sustainable long-term success [20]. Advanced monitoring systems, utilizing technologies such as GIS and remote sensing, offer precise tools for tracking habitat health and identifying areas in need of immediate attention. These tools provide actionable data that can inform conservation strategies and enable timely interventions. For instance, realtime data on land-use changes and deforestation activities can help prioritize

ISSN 2723-6471

reforestation efforts and the creation of ecological corridors, ensuring that conservation measures are both effective and efficient [21].

The integration of scientific research with local conservation practices underscores the importance of adaptive management in responding to dynamic environmental conditions. Protecting these ecosystems not only ensures the survival of this iconic species but also supports broader environmental goals, including biodiversity conservation, climate change mitigation, and the provision of ecosystem services. One important research area in this conservation effort is Curiak Island in South Kalimantan, which has been the focus of various proboscis monkey preservation initiatives. By aligning local actions with global sustainability objectives, we can create a resilient framework for the conservation of proboscis monkeys and the wetland ecosystems they depend on. This comprehensive strategy is vital for maintaining the health and balance of our planet's ecological systems, benefiting both wildlife and human communities for generations to come.

2. Methodology

This research employs a quantitative method to assess the health of proboscis monkey habitats using realtime and spatial data analysis. The research location includes wetland habitats such as gelam swamp ecosystems, peat swamps, and mangrove forests along riverbanks, particularly in Curiak Island, South Kalimantan. The study aims to understand the conditions of vegetation, temperature, humidity, and other environmental parameters essential for the survival of proboscis monkeys.

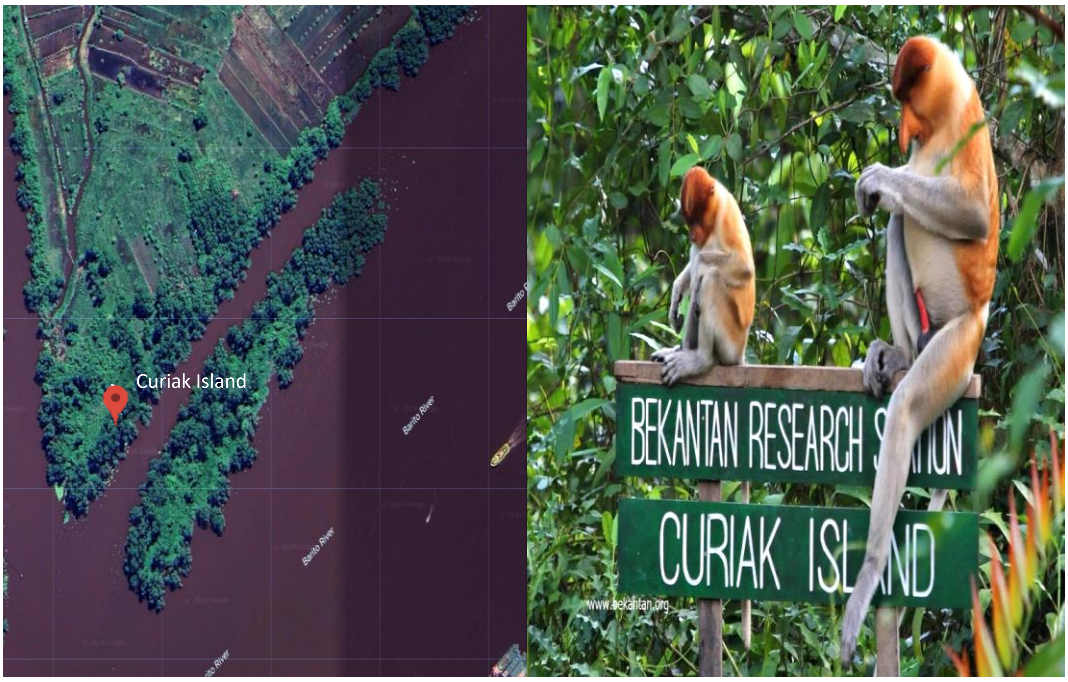

Figure 1. Map of Research Locations in Curiak Island South Kalimantan. Curiak Island in the Barito River delta is a conservation site for proboscis monkeys.

Figure 1 presents the research location map, which illustrates the specific areas of Curiak Island and its surrounding regions where the study was conducted. The map highlights the various wetland habitats that are critical for the proboscis monkeys. This comprehensive mapping is crucial for understanding the spatial distribution of vegetation, temperature, humidity, and other environmental parameters, thereby supporting the overall methodology of the research. By visualizing these areas, the map helps in identifying specific zones of interest and facilitates the targeted collection and analysis of data. The following steps outline the methodology used in this research:

2.1. Study Area and Sampling Sites

The research location encompasses both the core habitats of proboscis monkeys and the surrounding regions. This comprehensive approach ensures a better understanding of the environmental conditions affecting the monkeys. As illustrated in figure 1, the research location map includes key wetland habitats and surrounding areas to capture the impacts of The dataset consists of various numerical raster data types and IoT sensor data that are critical for environmental monitoring. Land Surface Emissivity (LSE), derived from Landsat 8, measures the Earth's surface's efficiency in emitting thermal radiation, calculated using the formula in the spatial data such :

1. Calculation the ECI

$$\mathrm{ECI}=\mathrm{LST} * \mathrm{BU} \quad (1)$$

Note : ECI is calculated by multiplying the with the Built-up Index (BU). It is used to assess the environmental condition in urban areas.

$$\mathrm{LSE} = 0.004 * \mathrm{FV} + 0.986 \quad (2)$$

Note : LSE is calculated using the Fractional Vegetation (FV) value.

$$LST = \frac{Tb}{1 + (0.00115 * \frac{Tb}{1.438} * \ln(LSE))} - 273.15 \quad (3)$$

Note : This formula is used to calculate LST from the brightness temperature (Tb) and LSE. It converts the temperature from Kelvin to Celsius.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (4)$$

Note : NDVI is used to assess vegetation health. It measures the difference between near-infrared (NIR) and red light reflectance.

$$NDBI = \frac{b7 - b5}{b7 + b5} \quad (5)$$

Note : NDBI (Normalized Difference Built-up Index) is used to detect built-up areas. It compares the reflectance values of Landsat bands 7 and 5.

$$\mathrm{BU} = \mathrm{NDBI} - \mathrm{NDVI} \quad (6)$$

Note : The BU is derived by subtracting NDVI from NDBI. It helps differentiate between built-up and vegetated areas

2. Calculation the VHI

$$\mathrm{VHI} = (0.5 * \mathrm{VCI} + 0.5 * \mathrm{TCI}) * 100 \quad (1)$$

VHI is calculated by combining the VCI and TCI. The weights (0.5 for each) indicate an equal contribution of both indices to the overall VHI. The result is then multiplied by 100 to scale the index. VHI is used to monitor vegetation health and detect drought conditions.

$$\mathrm{VCI} = \frac{\mathrm{NDVI} - \mathrm{NDVImin}}{\mathrm{NDVImax} - \mathrm{NDVImin}} \quad (2)$$

Note : VCI measures the relative condition of vegetation by comparing the current NDVI value to its historical minimum and maximum values. This index helps in assessing the impact of drought on vegetation.

$$\mathrm{TCI} = \frac{\mathrm{LSTmax} - \mathrm{LST}}{\mathrm{LSTmax} - \mathrm{LSTmin}} \quad (3)$$

Note : TCI evaluates the thermal condition of a region by comparing the current LST to its historical minimum and maximum values. TCI helps to identify areas experiencing heat stress, which can impact vegetation health.

2.1.1. Remote Sensing and GIS.

Advanced remote sensing technologies and GIS are utilized to collect spatial data on land-use changes, deforestation, and habitat degradation. Satellite imagery from sources like Landsat 8 is used to monitor changes in vegetation cover and land surface temperature over time. Additionally, Google Earth Engine (GEE) is employed to streamline the analysis of vast amounts of satellite data. GEE facilitates the processing of multi-temporal datasets, enabling the detection of changes in the environment with high accuracy [9]. By using GEE, researchers can apply various indices such as NDVI, NDBI, and others to large datasets, enhancing the efficiency and effectiveness of the remote sensing analysis.

2.1.2. Pre-Processing of Imagery

This stage includes image correction and cropping based on the study area. Radiometric correction is conducted to minimize atmospheric disturbances during image acquisition using the NDVI Analysis. GEE is used to automate the pre-processing steps [12], including atmospheric correction, cloud masking, and image mosaicking. This ensures that the data is consistent and ready for analysis. The study area is then cropped according to the administrative boundaries of the coal mining region to obtain detailed data. The use of GEE significantly reduces the time and effort required for pre-processing, ensuring that high-quality data is available for further analysis [20]. For the BU, the NDBI [21], Land Surface Temperature (LST), and Land Surface Emissivity (LSE), specific pre-processing steps are conducted to enhance accuracy. The NDBI involves selecting bands that correspond to the shortwave infrared (SWIR) and near-infrared (NIR) channels, followed by radiometric correction and cloud masking to ensure the data reflects true surface conditions. The BU is calculated by subtracting the NDVI from the NDBI [20], [22], requiring accurate correction and synchronization of both NDVI and NDBI data in terms of spatial resolution and temporal consistency. Pre-processing of LST data involves converting thermal infrared (TIR) sensor data into temperature values, with atmospheric correction being critical to remove the effects of atmospheric absorption and emission. GEE automates these corrections, ensuring the LST values accurately represent ground temperatures. The LSE is derived from the NDVI and fractional vegetation cover (FV), with pre-processing involving the correction of NDVI data and accurate calculation of FV, as any errors in these values will propagate into the LST results [13].

2.1.3. Image Processing

Data processed at this stage include the greenness index using NDVI by utilizing the Infrared and Near-Infrared channels. Google Earth Engine is leveraged to perform these calculations efficiently across large temporal and spatial scales. The NDVI values are classified based on greenness index ranges, which are then used to place sample plot points for field observation activities. Additionally, surface soil temperature and urban heat island indices are processed using GEE, allowing for the integration of multiple datasets and the generation of comprehensive environmental insights. GEE's powerful computational capabilities enable the handling of complex processing tasks, making it a crucial tool in this research. For BU, NDBI, LST, and LSE, GEE facilitates the complex calculations and mapping required. By using GEE for these complex calculations, the research ensures high accuracy and efficiency in data processing, enabling comprehensive environmental analysis and informed decision-making for conservation efforts.

2.1.4. Environmental Parameters

Data on vegetation health, temperature, and humidity are collected using the Vegetation Health Index (VHI) and Environmental Critical Index (ECI). VHI integrates the Vegetation Condition Index (VCI) and Temperature Condition Index (TCI) to assess vegetation stress, while ECI combines data on land surface temperature and vegetation cover to identify areas at risk of environmental degradation. The use of Google Earth Engine facilitates the continuous monitoring and updating of these indices, providing realtime insights into environmental conditions and helping in the early detection of potential degradation.

2.2. Field Observations

Field observations are conducted to validate the remote sensing data and collect additional information on the physical and biological conditions of the habitats. Internet of Things (IoT) technology plays a crucial role in enhancing the accuracy and comprehensiveness of these observations. Various sensors are deployed across the study area to continuously monitor environmental parameters such as CO, CO2, O2 levels, temperature, humidity, pH, dissolved oxygen (DO), total dissolved solids (TDS), and turbidity. These IoT sensors provide realtime data, enabling researchers to capture dynamic changes in environmental conditions that may affect the proboscis monkey habitats. The integration of IoT technology allows for the collection of high-resolution temporal and spatial data, which is essential for understanding the complex interactions between environmental variables and habitat health. This continuous monitoring capability helps in identifying trends and anomalies promptly, facilitating timely interventions and adaptive management strategies. By leveraging IoT, the research ensures a robust dataset that complements remote sensing observations, providing a holistic view of the ecosystem and supporting more effective conservation efforts. Specific field observation points on Curiak Island include coordinates -3.229550, 114.541261; -3.225180, 114.545289; and -3.230413, 114.540643. These coordinates are strategically chosen to capture a diverse range of environmental data, representing different parts of the habitat. The data collected from these points is crucial for validating the remote sensing data, ensuring that the satellite imagery and indices accurately reflect the ground conditions. The IoT sensors' continuous data stream allows for a detailed temporal analysis of environmental parameters, which is vital for detecting changes over time and understanding the factors driving these changes. For instance, fluctuations in water quality parameters like pH, DO, TDS, and turbidity can provide insights into the impacts of human activities and natural processes on the wetland ecosystems. Similarly, variations in CO and CO_2 levels can indicate changes in the carbon cycle and potential stressors to the vegetation. By integrating IoT technology with traditional field observations and remote sensing data, the research team can develop a comprehensive understanding of the environmental dynamics in the study area. This approach not only enhances the accuracy of the data collected but also provides a robust foundation for developing effective conservation strategies to protect the proboscis monkey habitats and ensure their long-term sustainability. Additionally, the research tracks the growth of the proboscis monkey population in the Curiak Island Research Station [2], [23], with numbers increasing from 14 individuals in 2016 to 50 in 2024 based on the Annual Report of the Sahabat Bekantan Indonesia Foundation (2016-2024), highlighting the success of habitat restoration efforts, including the planting of *Sonneratia caseolaris* or with the local name known as Mangrove Rambai as the main food source for the proboscis monkey. The other species trees such as Galam (*Melaleuca leucodendron*), Putat (*Planchonia valida*), and Jingah (*Gluta renghas*) are also planted in the restoration area for the enrichment of the vegetation structure.

2.3. Social and Institutional Analysis

The social and institutional conditions around the habitat areas are also considered. Surveys and interviews with local communities and stakeholders are conducted to understand their interactions with the environment and their roles in conservation efforts. This information is crucial for developing community-based conservation strategies. Understanding the social dynamics and institutional frameworks that govern the interactions between humans and the environment is essential for implementing effective conservation policies. By involving local communities in the research process, the study gains valuable insights into traditional ecological knowledge and practices that can complement scientific data. This participatory approach ensures that conservation strategies are culturally appropriate and more likely to be accepted and sustained by the community.

Local institutions, including government agencies, non-governmental organizations such Sahabat Bekantan Indonesia (SBI) Foundation, and community groups, play a pivotal role in environmental management and conservation [24]. The analysis of institutional structures helps identify key stakeholders and their influence on conservation outcomes. This analysis also highlights potential areas of conflict or cooperation that can impact the effectiveness of conservation efforts. Engaging with these institutions provides a platform for dialogue and collaboration, fostering a sense of shared responsibility and commitment to protecting the proboscis monkey habitats. Furthermore, understanding the socio-economic factors that drive land-use changes and habitat degradation is critical for developing targeted interventions. Economic activities such as agriculture, mining, and urban development significantly influence the environment. For instance, planting *Sonneratia caseolaris* can help in habitat restoration efforts, providing both ecological benefits and potential economic opportunities for local communities. By assessing the economic incentives and pressures faced by local communities, the study can propose alternative livelihood options that align with conservation goals. This approach not only addresses the root causes of habitat degradation but also promotes sustainable development and improves the well-being of local populations.

2.4. Data Analysis

2.4.1. Spatial Analysis

GIS tools are used to analyze the spatial distribution of environmental parameters. Spatial correlations between habitat conditions and proboscis monkey populations are examined to identify critical areas that require conservation efforts. This analysis involves overlaying various spatial datasets, such as vegetation cover, land surface temperature, built-up areas, and water quality parameters, to create a comprehensive map of the study area. By visualizing these spatial relationships, researchers can identify patterns and hotspots of environmental stress that may threaten the proboscis monkey habitats. For instance, in a similar conservation project in Sumatra, GIS tools were used to identify critical areas for the Sumatran tiger by overlaying spatial data on forest cover, prey density, and human disturbance [24]. This approach successfully pinpointed regions where conservation efforts were most needed, leading to targeted interventions that significantly improved habitat quality and connectivity for the tigers. Applying this methodology, the current study uses GIS to identify habitat corridors and connectivity between different patches of suitable habitat for proboscis monkeys. Maintaining habitat connectivity is crucial for the genetic diversity and long-term survival of the proboscis monkey populations. GIS tools enable the modeling of potential movement pathways and barriers, helping to inform conservation planning and the designation of protected areas. By integrating spatial analysis with field observations and remote sensing data, the study provides a robust framework for prioritizing conservation actions and optimizing resource allocation. For example, areas identified as high-stress zones due to fragmented vegetation and high land surface temperatures can be prioritized for restoration and protection, ensuring effective use of resources and better outcomes for conservation efforts.

2.4.2. Temporal Analysis

Temporal changes in vegetation health, temperature, and other parameters are analyzed to assess the impact of human activities over time. Time-series analysis helps in understanding trends and patterns in habitat degradation and recovery. This analysis involves the use of historical satellite imagery and ground-based data to track changes in environmental conditions over several years or decades. By examining these temporal dynamics, researchers can identify periods of significant change and correlate them with specific events or policies. For example, the implementation of the 2011 moratorium on deforestation in Indonesia had a significant impact on forest cover and habitat conditions [25]. By analyzing satellite images from before and after the moratorium, researchers observed a notable decrease in the rate of deforestation, which positively affected the habitat quality for many species, including proboscis monkeys. Similarly, the introduction of sustainable palm oil certification in the early 2000s aimed to reduce the environmental impact of palm oil plantations, leading to improved management practices and reduced habitat destruction. Temporal analysis also helps in evaluating the effectiveness of conservation interventions. By comparing pre- and post-intervention data, the study can assess whether the implemented measures have led to improvements in habitat conditions and proboscis monkey populations. This feedback loop is essential for adaptive management, allowing conservation strategies to be adjusted based on observed outcomes and new information. Additionally, temporal analysis provides insights into the resilience of the ecosystem to environmental disturbances. Understanding how the habitat responds to natural and anthropogenic stressors over time helps predict future changes and develop proactive conservation measures. For instance, analyzing the recovery of vegetation following major forest fires or logging activities can reveal the ecosystem's capacity to regenerate and the timeframe required for recovery. By integrating temporal and spatial analyses, the study offers a comprehensive understanding of the factors driving habitat changes and the strategies needed to mitigate their impacts. This holistic approach ensures that conservation efforts are informed by both historical and current data, leading to more effective and sustainable management of proboscis monkey habitats.

2.5. Final Output Presentation

This research involves a multi-stage process comprising several key activities: initially, data collection is undertaken to gather relevant information. This includes collecting satellite imagery, environmental sensor data, and field observations of vegetation and wildlife conditions. Subsequently, pre-processing of the data is conducted to ensure its quality and suitability for analysis, including noise reduction, calibration, and alignment of different data sources. The core phase of data processing follows, wherein the data is systematically analyzed using appropriate methodologies. Concurrently, field activities are carried out to validate and complement the collected data. These field activities include ground-truthing exercises where data collected in the field is compared against remote sensing data to verify accuracy. For example, measurements of vegetation health and land surface temperature taken directly in the field are used to validate the corresponding satellite-derived indices. Regular field surveys are also conducted to monitor proboscis monkey populations and their habitats, providing crucial contextual information that supports the data analysis. Finally, a thorough data analysis is performed, culminating in the creation of a comprehensive research report that encapsulates the findings and insights derived from the entire research process. This analysis includes spatial and temporal analysis to assess changes in habitat conditions and the effectiveness of conservation measures. An ongoing monitoring system is established to continuously track the health of proboscis monkey habitats. Realtime data from remote sensing and field observations are integrated to provide timely information for conservation interventions. Evaluation of the effectiveness of conservation strategies is conducted periodically to ensure adaptive management, thereby enhancing the overall efficacy of the conservation efforts. This includes re-assessing habitat conditions, comparing them with baseline data, and making necessary adjustments to conservation practices based on the findings. By incorporating rigorous data validation and detailed field activities, the research ensures that the findings are credible and actionable, providing a robust foundation for effective conservation planning and implementation.

3. Results and Discussion

3.1. Result Analysis of Curiak Island

To obtain information based on the results from spatial analysis on satellite data and field measurement results, a comprehensive process involving several steps is conducted. Initially, satellite images from Landsat and Sentinel are downloaded and subjected to radiometric and atmospheric corrections using GEE to ensure accuracy. Analysis process in GEE shows in figure 2.

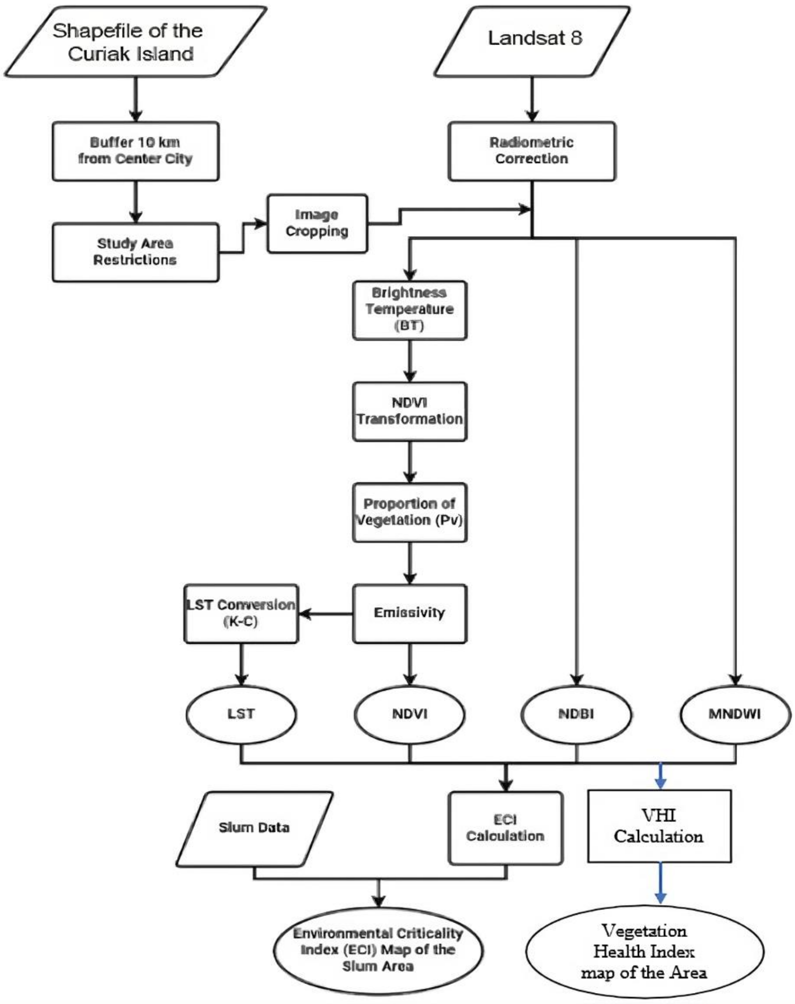

Figure 2. Flow Analysis Data for ECI and VHI

Indices such as LST, NDVI, NDBI, and BU are calculated to understand the distribution of land cover and land use changes on Curiak Island. LST is calculated to determine the surface temperature, which is then used to derive the VHI and the ECI. The ECI analysis results, indicated in yellow, highlight areas with varying degrees of environmental stress,

ISSN 2723-6471

reflecting the impact of factors such as urbanization and habitat degradation. The VHI analysis, indicated in green, shows the health and vitality of the vegetation, with higher values representing healthier vegetation. These analyses provide critical insights into the health of the vegetation and the overall environmental condition of Curiak Island, as shown in the spatial distribution maps in figure 2. Field measurement data is utilized to validate the satellite analysis results, ensuring their reliability.

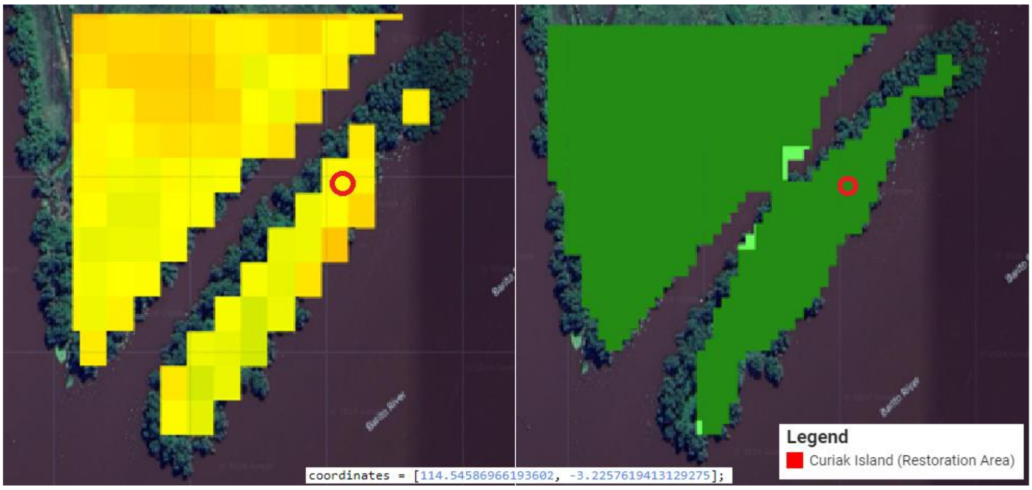

Figure 3. Condition of distribution ECI and VHI in Curiak Island

Figure 3 illustrates the distribution of the VHI and ECI in Curiak Island, with the right image showing ECI and the left image showing VHI. To enhance clarity, the ECI distribution is represented with a color scale where dark yellow indicates high environmental criticality, light yellow indicates moderate environmental criticality, and green indicates low environmental criticality. Similarly, the VHI distribution uses a color scale where dark green indicates high vegetation stress, light green indicates moderate vegetation stress, and bright green indicates low vegetation stress. These legends and color scales provide a clear interpretation of the data, showing areas with varying levels of vegetation health and environmental stress. We analyze the condition of Curiak Island where the result provided values represent the output from a script that calculates various environmental indices, crucial for understanding vegetation health and environmental conditions. The VHI value is 37.860687255859375, indicating the overall health of the vegetation within the analyzed area. VHI is a composite index that combines the VCI and the TCI, both of which are calculated separately. The VCI value is 0.30130425095558167, and it measures the current vegetation condition relative to its historical range. A lower VCI value suggests poorer vegetation health, potentially due to factors like drought or disease. The TCI value is 0.45590946078300476, which reflects the impact of temperature on vegetation health. Higher TCI values indicate better vegetation conditions under current temperature conditions. The result from VHI in curiak and restoration area show in figure 4.

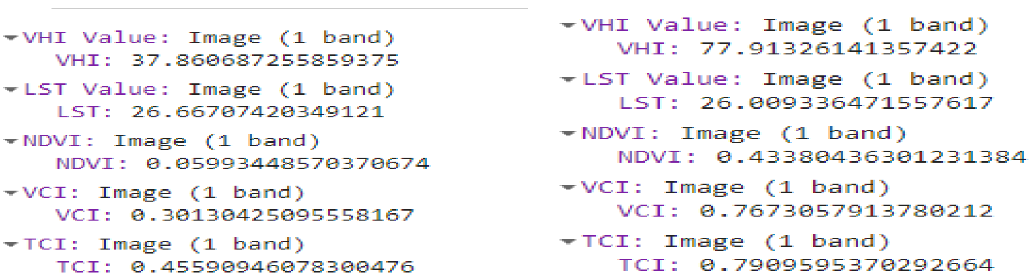

Figure 4. Analysis Result VHI in Curiak Island and Restoration Area

The comparison between the original analyzed area and the restoration area shows significant improvements in environmental indices in the restoration area. The VHI value in the restoration area is 77.91, indicating much healthier vegetation compared to the original area's VHI of 37.86. The VCI value of 0.77 in the restoration area reflects strong vegetation conditions relative to historical data, suggesting successful restoration efforts, compared to the original area's VCI of 0.30. Similarly, the TCI value of 0.79 in the restoration area indicates thriving vegetation under current temperature conditions, compared to the original area's TCI of 0.46. The LST value in the restoration area is slightly lower at 26.01°C, compared to 26.67°C in the original area, suggesting that restoration efforts may have helped moderate surface temperatures, creating a more favorable thermal environment for vegetation. Additionally, the NDVI value in the restoration area is significantly higher at 0.43, indicating denser and healthier vegetation cover compared to the original area's NDVI of 0.06. These findings collectively highlight the positive impact of restoration efforts on vegetation health and environmental conditions in Curiak Island.

In summary, these values provide a comprehensive overview of the environmental conditions affecting vegetation health in the analyzed region. The VHI value integrates both VCI and TCI to offer a nuanced view of vegetation health, considering both vegetation conditions and temperature effects. The LST value helps understand the thermal environment, while the NDVI value gives insight into vegetation density and health. Comparing the original area with the restoration area, it is evident that the restoration efforts have significantly improved the vegetation health and overall environmental conditions. These indices together are crucial for monitoring and managing vegetation health, informing conservation efforts, and understanding the impacts of environmental stressors on the ecosystem. This analysis can guide targeted interventions to improve vegetation health and mitigate adverse environmental conditions.

3.2. Vegetation Health Index Data Analysis

We analyze the changes in vegetation health from 2015 to 2023 to understand the historical results of our analysis. There are two analysis graphs created, one for the conservation area of the island and one for the restoration area. The following two graphs show the vegetation health conditions in two different areas: the restoration area and the overall island area on Curiak Island. This analysis is crucial for understanding the impact of restoration efforts and the broader environmental conditions to ensure the sustainability of the proboscis monkey habitat. The results are presented in figure 5.

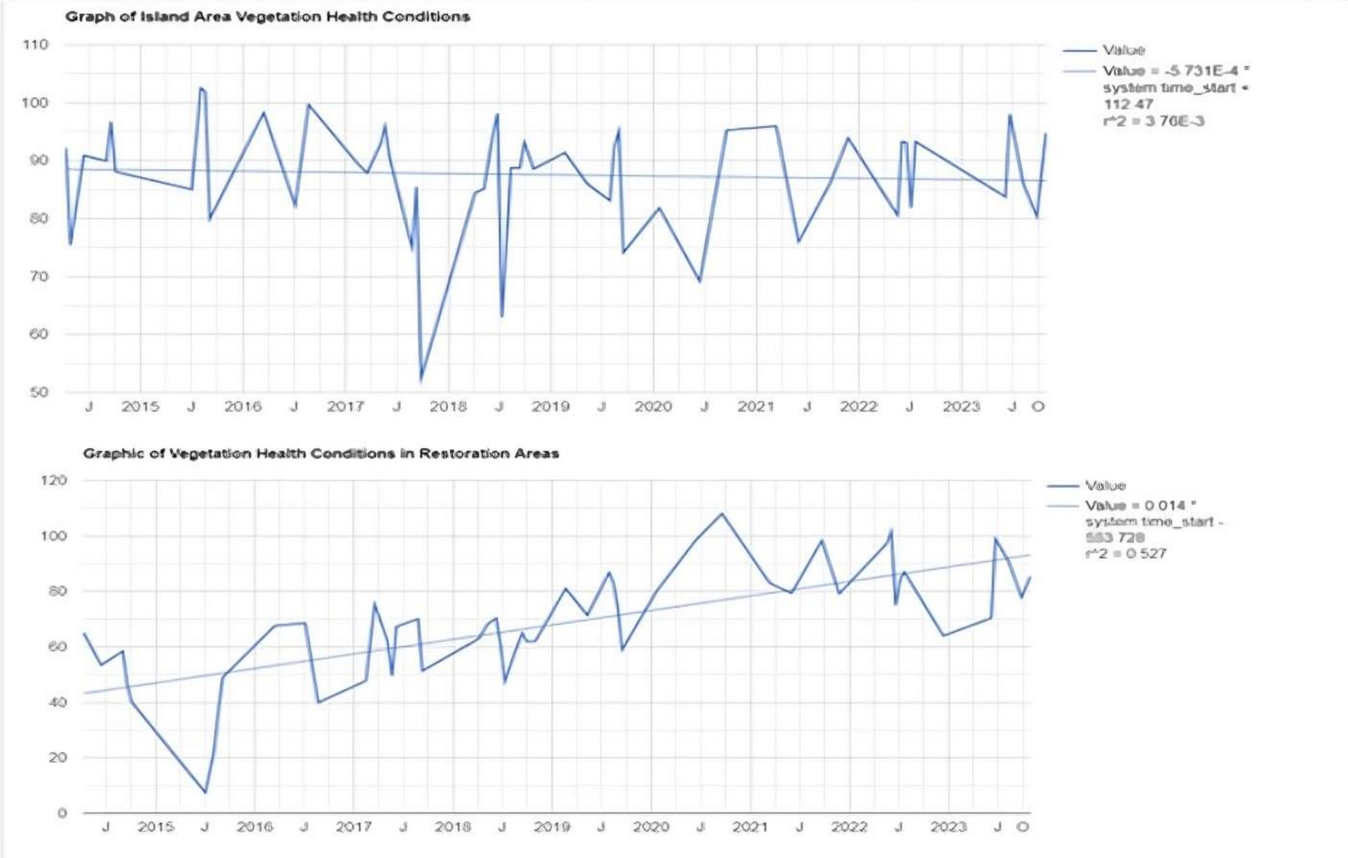

Figure 5. Analysis trend VHI in Curiak Island and restoration area

The two graphs above show the vegetation health conditions in two different areas: the restoration area and the overall island area on Curiak Island. Here are the results of the analysis obtained:

The first graph, titled "Graph of Island Area Vegetation Health Conditions," shows the trend of changes in vegetation health conditions across the entire Curiak Island area from 2015 to 2023. As in the first graph, the blue line represents VHI values over time, with a linear trend line added to help understand long-term changes. In this graph, it can be seen that the VHI values across the island tend to remain stable with a slight decline in recent years. The VHI values across the island range from 80-100, indicating relatively healthy vegetation conditions overall. However, the trend line shows a slight decline, suggesting some challenges or environmental pressures that might be affecting vegetation conditions in this area. This decline could be due to various factors such as climate change, urbanization, or other human activities that negatively impact the environment. For instance, increasing temperatures and irregular rainfall patterns due to climate change can stress vegetation. Additionally, urbanization and land-use changes can lead to habitat fragmentation and degradation, impacting overall vegetation health. These factors highlight the importance of ongoing monitoring and adaptive management to mitigate negative impacts and support vegetation health across the island.

The second graph, titled "Graphic of Vegetation Health Conditions in Restoration Areas," shows the trend of changes in vegetation health conditions in the restoration area from 2015 to 2023. The blue line represents VHI values over time, while the linear trend line is added to help understand long-term changes. VHI is a composite index that combines the VCI and the TCI to provide a more comprehensive view of vegetation health, considering both vegetation conditions and temperature effects. From this graph, it can be seen that the VHI values in the restoration area tend to increase over time, with some fluctuations. This upward trend indicates that restoration efforts have successfully improved the vegetation health conditions in the area. At the beginning of the period, VHI values were around 40-60, indicating moderate to poor vegetation conditions. However, over time, VHI values increased to around 80-100, indicating healthier vegetation conditions. This suggests that the vegetation in the restoration area has been improving and recovering from previously degraded conditions.

When comparing the two graphs, it is clear that restoration efforts in certain areas have significantly improved vegetation health conditions compared to the overall island area. The restoration area shows a significant upward trend in VHI values, while the island area shows a more stable but slightly declining trend. This difference indicates that the restoration interventions carried out in the restoration area have a tangible positive impact on vegetation health. This can be attributed to various restoration actions such as reforestation, erosion control, better water management, weed control efforts that hinder mangrove growth [2], and regular monitoring by the SBI community involving local community participation [25]. Data on the high level of community participation can be supported by quotes from the previous research [26]. Conversely, the overall island area may not have received the same intensive restoration interventions, thus showing more stable conditions but with some decline in vegetation health [24]. These data provide important insights for environmental managers and policymakers to focus on effective restoration actions and expand them to other areas that need environmental improvement. Additionally, continuous monitoring of vegetation health conditions is crucial to assess the effectiveness of restoration actions and adjust conservation strategies as needed. Overall, these graphs demonstrate that with proper restoration efforts, vegetation health conditions can be significantly improved, ultimately supporting the sustainability of the ecosystem and the well-being of communities that depend on the environment.

3.3. Environmental Condition Index Data Analysis

The provided data includes three key indices for the year 2023: NDVI, LST, and ECI. These indices are crucial for understanding the overall environmental conditions, particularly in the context of vegetation health and surface temperature. The results are presented in figure 6.

```
▾NDVI tahun 2023: Image (1 band)
   NDVI: 0.7288063478118239
▾LST tahun 2023: Image (1 band)
   LST: 20.754799180868417
▾ECI Masked 2023: Image (1 band)
   ECI: 53

▾NDVI tahun 2023: Image (1 band)
   NDVI: 0.6084833833459442
▾LST tahun 2023: Image (1 band)
   LST: 20.408015804649153
▾ECI Masked 2023: Image (1 band)
   ECI: 74
```

Figure 6. Analysis ECI in restoration area and Curiak Island

To understand the overall environmental health of the area from Figure 6, we analyzed three key indices for the year 2023: NDVI, LST, and ECI. The NDVI value in the restoration area is 0.73, higher than the general area's 0.61, indicating denser and healthier vegetation cover due to effective restoration efforts. The LST in the restoration area is slightly higher at 20.75°C compared to 20.41°C in the general area, which may result from increased vegetation density and evapotranspiration. The ECI value in the restoration area is 53, lower than the general area's 74, suggesting reduced environmental stress and successful mitigation of issues like soil degradation, pollution, and habitat fragmentation. This lower ECI value implies that restoration efforts have positively impacted the ecosystem, highlighting the importance of continuous monitoring and adaptive management. Future conservation strategies can leverage these insights to replicate successful restoration practices in other areas, ensuring the long-term sustainability and resilience of the ecosystem.

The NDVI value for 2023 is 0.6085, which indicates moderate vegetation density and overall healthy plant growth in the area. NDVI values range from -1 to 1, where values closer to 1 signify robust vegetation and values near -1 represent barren or unhealthy land. With an NDVI value of approximately 0.61, the ecosystem in this area appears well-maintained, supporting healthy vegetation growth. The LST for 2023 is 20.41°C, a moderate value that indicates favorable surface conditions for plant growth. LST is influenced by factors such as vegetation cover, moisture, and atmospheric conditions. Lower LST values are typically found in areas with abundant vegetation, as plants help cool the surface through transpiration. The ECI for 2023 is 74, which reflects a moderate level of environmental stress. The ECI combines various environmental factors to assess overall conditions, and a lower value signifies better environmental health. An ECI of 74 suggests that, while there are some challenges, the area is not facing severe environmental degradation but may have room for improvement in specific areas.

Comparison with Restoration Area Data, the restoration area data reveals several insights. The NDVI in the restoration area is higher at 0.73, indicating denser and healthier vegetation compared to the general area's 0.61. This suggests that restoration efforts have positively impacted vegetation health. However, the LST in the restoration area is slightly higher at 20.75°C compared to the general area's 20.41°C, which could be attributed to the more extensive vegetation cover causing localized daytime warming. Interestingly, the ECI in the restoration area is lower at 53 compared to 74 in the general area. While this may seem counterintuitive given the higher NDVI in the restoration area, it suggests that the restoration area, despite healthier vegetation, may still be recovering from other environmental stresses that affect the overall ECI. This highlights the complexity of environmental recovery, where improvements in one factor, like vegetation, do not immediately translate into lower overall environmental stress.

3.4.Interpretation and Implications

The data indicates that while the restoration area shows stronger vegetation health as indicated by the NDVI, the overall environmental condition as measured by ECI suggests that there are still other factors affecting the restoration area. The value of ECI in the restoration area which indicated the moderate environmental critically could be due to the fact that restoration efforts often focus initially on vegetation, and other environmental conditions may take longer to recover. In summary, the NDVI and LST data demonstrate successful vegetation growth and moderate surface temperatures in both areas, with the restoration area showing particularly robust vegetation. However, the value of ECI in the restoration area highlights the complexity of environmental recovery, suggesting that comprehensive restoration efforts must continue to address all aspects of environmental health. This comparative analysis provides valuable insights for environmental managers and policymakers to focus on holistic restoration strategies that not only improve vegetation health but also enhance the overall environmental conditions.

3.5. Realtime Data Analysis

We analyze the changes in environmental conditions using realtime data collected through IoT technology. This technology allows us to continuously monitor various environmental parameters, providing up-to-date information on vegetation health and other factors. Two analysis graphs have been created: one for the overall island area of Curiak and one for the restoration area. These graphs show the vegetation health conditions in these two different areas, helping to understand the impact of restoration efforts and the broader environmental conditions. This realtime data analysis is crucial for ensuring the sustainability of the proboscis monkey habitat. The results are presented in figure 7.

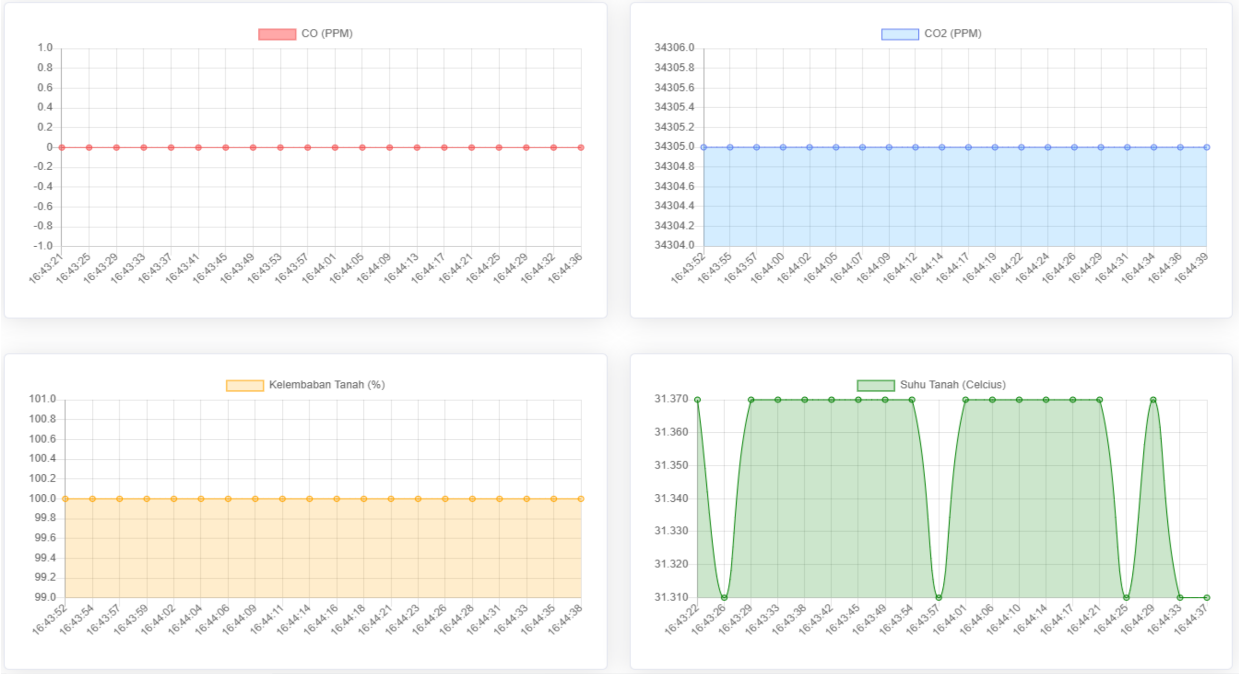

Figure 7. Analysis realtime data using IoT in Curiak Island and restoration area (CO, CO2, PM10, PM2.5, O2, DO, PH, TSS)

The realtime data results for the Curiak Island area and restoration area indicate stable environmental conditions with some notable variations. Carbon monoxide (CO) levels are consistently low, around 0.2 PPM, suggesting minimal pollution. Carbon dioxide (CO_2) levels show a slight downward trend at approximately 34,045 PPM, indicating potentially lower respiration rates or reduced anthropogenic activity. Soil moisture content remains high, around 100%, indicating effective water retention crucial for vegetation health. Soil temperature fluctuates between 32.825°C and 32.880°C, reflecting daily changes and the importance of microclimate regulation. Particulate matter levels (PM10 and PM2.5) show some variability, with PM10 ranging from 23.0% to 25.5% and PM2.5 around 24.6%, suggesting the presence of particulate matter that could be from natural or anthropogenic sources. The pH levels stabilize around 6.8, indicating neutral to slightly acidic conditions, which are generally favorable for most plant and aquatic life. Air humidity and temperature exhibit minor fluctuations, with humidity between 67.45% and 67.65% and temperature between 33.155°C and 33.185°C, which are typical of tropical environments and crucial for maintaining ecosystem stability. Oxygen levels are steady at 20.4% Vol, essential for aerobic respiration and indicating healthy atmospheric conditions. Dissolved oxygen (DO) levels show stability, critical for aquatic life sustainability. Total suspended solids (TSS) and turbidity levels are stable, indicating consistent water clarity, important for photosynthesis and aquatic habitat health.

The stability of these environmental parameters suggests that current conservation efforts are effectively maintaining the habitat conditions necessary for the proboscis monkey population. The consistently low levels of pollutants and stable water quality metrics indicate a healthy environment. The observed variations in particulate matter and soil temperature highlight areas for further monitoring and potential intervention to ensure these factors do not negatively impact the ecosystem. Continuous realtime monitoring allows for timely identification and mitigation of emerging environmental threats, ensuring adaptive management strategies can be implemented promptly. These insights are crucial for informing future conservation actions, maintaining the sustainability of the habitat, and supporting the long-term health of the proboscis monkey population on Curiak Island.

4. Conclusion and Recommendations

4.1. Conclusion

This research develops a real-time and spatial data analysis-based monitoring system to enhance the effectiveness of conservation area management for proboscis monkey habitats in Curiak Island, South Kalimantan. The results indicate that restoration efforts have significantly improved vegetation health, with an NDVI value of 0.7288 and a lower LST of 20.75°C in the restoration area, compared to an NDVI of 0.6085 and LST of 20.41°C in the general area. The ECI shows the restoration area is still recovering from other environmental stresses, with a value of 53 compared to 74 in the general area. Real-time data from IoT sensors indicate stable environmental conditions with minimal variations in CO, CO2, O2, temperature, humidity, pH, dissolved oxygen (DO), total dissolved solids (TDS), and turbidity. This comprehensive monitoring system provides valuable insights to support timely and adaptive conservation interventions, ensuring the sustainability of proboscis monkey habitats.

Furthermore, the integration of advanced remote sensing and GIS technologies with IoT-based environmental monitoring has demonstrated its effectiveness in providing continuous, real-time data. This approach has enabled the identification of critical areas needing immediate conservation actions and allowed for the evaluation of restoration progress over time. By employing indices such as NDVI, VCI, TCI, and ECI, this study has highlighted the importance of maintaining healthy vegetation and optimal temperature conditions for the survival of proboscis monkeys. The involvement of local communities in conservation efforts has also proven to be vital. Their participation not only enhances the effectiveness of the conservation strategies but also fosters a sense of stewardship towards natural resources. The study's findings underscore the need for a multifaceted approach that combines scientific research, technological innovation, and community engagement to address the complex challenges of habitat conservation. The continuous monitoring and adaptive management strategies recommended in this study are essential for the long-term success of conservation efforts, providing a robust framework for protecting the proboscis monkey habitats and ensuring the ecological health of the region.

4.2. Recommendations

To ensure the future success of proboscis monkey habitat conservation, several strategic steps must be taken. First, expanding restoration areas and intensifying efforts to plant local vegetation species, such as Sonneratia caseolaris (mangrove rambai), can help increase NDVI values and lower LST, creating better environmental conditions. Second, integrating more advanced remote sensing technologies and improving spatial data analysis algorithms will allow for real-time monitoring of subtle environmental changes, enabling more accurate interventions. Third, increasing local community participation through education and training programs will enhance conservation efforts by incorporating local knowledge and traditional practices, ensuring long-term sustainability. Additionally, developing ecological corridors to connect fragmented habitats will promote movement and genetic exchange among proboscis monkey populations, maintaining genetic diversity and resilience to environmental changes. By implementing these strategies and continuing to develop adaptive, data-driven approaches, the conservation of proboscis monkey habitats can become more effective and contribute to the sustainability of wetland ecosystems and biodiversity.

5. Declarations

5.1. Author Contributions

Conceptualization: A.N., K., A.R., and M.; Methodology: K.; Software: A.N.; Validation: A.N., K., A.R., and M.; Formal Analysis: A.N., K., A.R., and M.; Investigation: A.N.; Resources: K. and A.R.; Data Curation: K.; Writing Original Draft Preparation: A.N., K., A.R., and M.; Writing Review and Editing: K., A.N., A.R., and M.; Visualization: A.N.; All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Institutional Review Board Statement

Not applicable.

5.5. Informed Consent Statement

Not applicable.

5.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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