Monitoring Water Turbidity in the Chiang Rai Reach of the Mekong River Using Sentinel-2 NDTI

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Abstract

The Mekong River plays a vital role in regional ecology, food security, and water governance, yet turbidity monitoring in its upper reaches remains limited. The Chiang Rai sector, located at the first upstream entry point of the Lower Mekong Basin, functions as a sediment and flow gateway to downstream countries; however, no systematic satellite-based turbidity assessment has previously been conducted for this area. This study addresses this gap by applying the Normalized Difference Turbidity Index (NDTI) derived from Sentinel-2 MSI imagery to investigate spatial and seasonal turbidity dynamics from 2019 to 2024. Multi-temporal satellite datasets were processed using Google Earth Engine and integrated with monthly rainfall (TerraClimate) and water surface area extracted using the Modified Normalized Difference Water Index (MNDWI). Results revealed a clear monsoonal pattern, with turbidity peaking between June and September and declining during the dry season (November-April). Regression analysis showed a moderate correlation between rainfall and turbidity ($R^2 = 0.37$), while a stronger association with water surface area ($R^2 = 0.514$) indicates the dominant influence of hydromorphological processes such as sediment resuspension and floodplain connectivity. Although the absence of field-based turbidity measurements represents a key limitation, the findings demonstrate the potential of Sentinel-2 -based NDTI as a cost-efficient monitoring tool in data-scarce transboundary basins. This study provides the first satellite-derived turbidity baseline for the northern Mekong and offers a practical framework to support basin-wide water-quality monitoring and policy decision-making under increasing hydropower regulation and climate variability.

Keywords: Mekong River, NDTI, MNDWI, Sentinel-2, TerraClimate

1. Introduction

The Mekong River is a major transboundary river system supporting regional ecosystems, agriculture, fisheries, navigation, and domestic water supply across six countries in Southeast Asia [1]. Beyond its socio-economic importance, the river functions as a dynamic sediment-water system in which turbidity plays a key role in controlling water quality, aquatic habitat conditions, and sediment transport processes [2]. The Chiang Rai reach in Northern Thailand represents the first upstream section of the Lower Mekong Basin and serves as the primary entry point where sediment loads, and hydrological conditions begin to propagate downstream into Laos, Cambodia, and Vietnam. Because of this upstream influence, changes in turbidity within this sector have basin-wide implications for river morphology, fisheries productivity, and transboundary water governance. Although previous studies have examined turbidity in various parts of the Lower Mekong Basin [3-5].

Most rely on sparse and spatially discontinuous in-situ measurements, which are insufficient for capturing rapid hydrological changes and seasonal sediment pulses [6]. Findings from other large Asian rivers (e.g., Ganges, Yangtze) confirm that turbidity and suspended sediment concentration (SSC) can vary sharply within a single monsoon cycle, highlighting the limitation of field-only datasets [4,7]. Despite this, no study has yet provided a satellite-based turbidity assessment for the Chiang Rai reach, leaving a critical upstream monitoring gap in the Mekong River system.

To address these monitoring gaps, numerous studies have confirmed that satellite remote sensing provides a reliable and efficient means of evaluating water turbidity across diverse hydrological settings, including large rivers [3,5], reservoirs and dams [4,8], lakes and coastal waters [7,9,10], and small inland water bodies [11]. High-resolution, frequently acquired satellite imagery enables consistent observation, making the Normalized Difference Turbidity Index (NDTI) an effective tool for monitoring turbidity in large, highly dynamic water bodies.

For example, at the Panchet Dam in India, turbidity rose sharply from 60 NTU to 700 NTU during the monsoon season. At its peak, highly turbid water covered more than 64 % of the reservoir, and the Landsat-8-derived NDTI showed a strong correlation with suspended sediment concentration (SSC) (R^2 = 0.90, RMSE = 13.59) [4]. Elhag et al. [8] used Sentinel-2 imagery to monitor water quality in the Wadi Baysh Dam (2017–2018). Field measurements showed strong correlations between satellite-derived indices and in-situ data chlorophyll a with MCI (R^2 = 0.96), nitrate with GNDVI (R^2 = 0.94), and turbidity with NDTI (R^2 = 0.94) demonstrating that Sentinel-2 provides an effective tool for assessing water quality in arid environments. Nontapon et al. [3] reported that Landsat-8 analysis of the Mekong River showed the NDSSI to be the most accurate index for estimating SSC (R^2 = 0.723, RMSE = 20.2 mg L^{-1}), whereas NDTI was less reliable (R^2 = 0.418, RMSE = 27.5 mg L^{-1}). Kolli & Chinnasamy [5] found that, in the highly dynamic Godavari River of India, Sentinel-2 imagery revealed that a red-edge single-band algorithm provided the most accurate turbidity estimates (R^2 = 0.91, RMSE = 0.003), outperforming NDTI (R^2 = 0.85, RMSE = 0.05). Li et al. [7] demonstrated the importance of long-term monitoring: a 30-year time series (1990-2020) of Landsat-5, Landsat-7, and Landsat-8 images for China's Chao Lake showed NDTI values increasing by more than 242 %, indicating intensified sedimentation and declining water quality. Dabire et al. [9] analyzed Sentinel-2 surface-reflectance data to compute NDTI and the Normalized Difference Chlorophyll Index (NDCI), reporting NDTI values from -0.045 to 0.0723 and NDCI values from -0.016 to 0.019, with the highest pollution detected along the shoreline. Ardyan [10] used Sentinel-2A imagery of Jakarta Bay, Indonesia, processed in Google Earth Engine, to calculate NDTI and Total Suspended Solids (TSS). Analysis of five observation points revealed clear spatial variation: Point 1 recorded the highest turbidity (NDTI = 0.21; TSS = 46.81 mg L^{-1}), Point 5 the lowest, and Point 3 the highest NDTI (0.23) but only 23.49 mg L^{-1} TSS, indicating finer suspended particles. Lacaux et al. [11] employed 10 m-resolution SPOT-5 imagery over the Ferlo region of Senegal, using the NDPI and NDTI indices to map small ponds. They found that ponds smaller than 0.5 ha accounted for 65–90 % of total pond area and that potential Rift Valley Fever mosquito habitat covered up to 25 % of the region during the rainy season. For Lake Nokoue in Benin.

These studies demonstrate that although the Normalized Difference Turbidity Index (NDTI) is highly useful for assessing water turbidity across a wide range of aquatic environments-including large rivers, reservoirs, lakes, and coastal waters-its performance is not uniformly consistent. Multiple factors, such as watershed characteristics, seasonal variations, upstream sediment loads, and human activities, can influence the accuracy of NDTI, leading to regional differences in assessment results. In many cases, long-term monitoring is essential to capture sedimentation trends and ongoing changes in water quality. Continuous observation over extended periods also helps identify seasonal or anthropogenic patterns of turbidity variation, such as those driven by dam construction, agricultural practices, or urban expansion, providing critical information for water-resource management and sustainable environmental planning.

Research on the Chiang Rai reach of the Mekong River remains limited, despite its role as a critical upstream gateway of the Lower Mekong Basin where sediment transport and turbidity dynamics directly influence downstream water quality and regional food security. Applications of Sentinel-2–derived NDTI for this area are still scarce, and comprehensive evaluations integrating temporal and seasonal turbidity variations with spatial and seasonal heterogeneity have yet to be undertaken. Addressing these gaps is essential to advance understanding of spatio-temporal turbidity processes and to establish a cost-effective, satellite-based monitoring framework that complements conventional field observations. This study is based on the hypothesis that the NDTI from Sentinel-2 imagery can effectively reflect both the spatial and seasonal variability of water turbidity in the Mekong River within Chiang Rai Province. Higher turbidity is expected during the monsoon season due to increased sediment loads. The objectives of this research are: 1 to analyze the spatial distribution of turbidity using Sentinel-2 NDTI, and 2 to examine temporal and seasonal changes in turbidity patterns in the Mekong River within Chiang Rai Province.

2. Research Methodology

2.1 Study Area

The study was conducted in the Mekong River within Chiang Rai Province, northern Thailand. This section is a critical upstream reach of the Lower Mekong Basin, where hydrological flow and sediment transport strongly influence downstream water quality and aquatic ecosystems. Chiang Rai Province is located in a mountainous region, with elevations ranging from approximately 300 meters along the river plains to over 1,500 meters in the surrounding highlands. This topography contributes to rapid surface runoff and soil erosion, particularly during heavy rainfall, which increases sediment transport into the Mekong River.The climate of Chiang Rai is classified as tropical monsoon, consisting of three distinct seasons: a cool-dry season (November-February), a hot-dry season (March-May), and a rainy season (June-October). The average annual rainfall ranges between 1,200-1,600 mm, with the majority occurring during the monsoon period. Air temperatures generally range from 15-25 °C during the cool season to 25–35 °C in the hot season, with an annual mean temperature of about 24 °C. These climatic and topographic characteristics play a significant role in shaping the hydrological dynamics and turbidity variability of the Mekong River within Chiang Rai Province (see Figure 1).

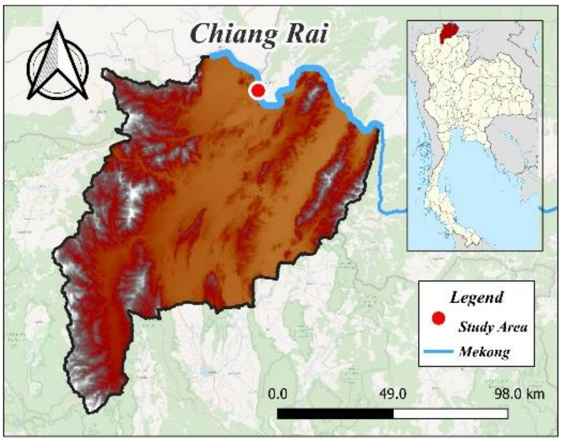


Figure 1 Location of the study area in the Mekong River at Chiang Rai Province, Northern Thailand.

2.2 Data Sources

This study employed multi-source datasets to monitor water turbidity in the Mekong River within Chiang Rai Province. Sentinel-2 MSI Level-2A surface reflectance imagery (COPERNICUS/S2_SR_HARMONIZED) from January 2019 to December 2024 was used, focusing on the Green (B3, 560 nm), Red (B4, 665 nm), and SWIR1 (B11, 1610 nm) spectral bands, with a spatial resolution of 10-20 m. and a revisit frequency of approximately five days. The data were processed and analyzed on the Google Earth Engine (GEE) platform [12] (accessed on August 25, 2025). From these data, the MNDWI was calculated to delineate water bodies, and the NDTI was applied as a proxy for turbidity. Monthly precipitation data were obtained from the TerraClimate dataset (*IDAHO_EPSCOR/ TERRACLIMATE*) with 4.6 km resolution for the same period, providing climatic context [13].

Ancillary datasets included river boundary shapefiles for clipping and hydrological statistics from the Thai Meteorological Department and the Mekong River Commission for contextual interpretation. Cloud and shadow masking was performed using the Sentinel-2 Scene Classification Layer (SCL), with additional filtering based on the cloud probability layer (CLOUD_PROBABILITY < 20%). Preprocessing steps consisted of atmospheric correction (Level 2A), cloud and shadow removal, spatial clipping to the study area, and the generation of monthly median composites. A water mask with an MNDWI threshold greater than 0.1 was applied to ensure NDTI calculations were restricted to water pixels only.

2.3 Index Calculation

In this study, the NDTI was applied as the primary indicator of water turbidity [14]. The NDTI was calculated using the Red (B4) and Green (B3) bands of Sentinel-2 imagery according to the following Equation (1).

$$\text{NDTI}=\frac{\text{Red-Green}}{\text{Red+Green}} \quad (1)$$

Where Red is Band 4
Green is Band 3

This index was used as a turbidity proxy to detect suspended sediments and water quality changes, while monthly rainfall data (mm/month) from the TerraClimate dataset for the same period provided hydrological context for interpreting turbidity variability.

2.4 Monthly Aggregation and Statistical Analysis

For each month between January 2019 and December 2024, Sentinel-2 imagery was processed to generate monthly median composites, minimizing the effects of cloud contamination and temporal noise. The NDTI was calculated for each composite and masked using the MNDWI to ensure that turbidity measurements were restricted to water pixels only [15]. The MNDWI was computed from Sentinel-2 bands according to Equation (2).

$$\text{mNDWI}=\frac{\text{Green-SWIR1}}{\text{Green+SWIR1}} \quad (2)$$

Where Green is Band 3
SWIR1 is Band 11

Descriptive statistics including the mean, median, and standard deviation of NDTI were then computed within the study area to evaluate spatial and temporal variability in water turbidity. Water surface area was also estimated in both square meters and square kilometers using pixel area values where MNDWI exceeded 0.1. To provide hydrological context, monthly precipitation data from the TerraClimate dataset were averaged across the study area. Finally, all outputs-including NDTI statistics, water surface area, and rainfall data-were exported as Comma-Separated Values (CSV) files to support subsequent statistical and comparative analyses.

2.5 Visualization and Analysis

The visualization and analysis focused on examining the spatial and temporal variations of turbidity in the Mekong River throughout the study period. Time-series charts were generated to illustrate monthly changes in the NDTI, water surface area, and rainfall, which clearly highlighted seasonal differences between the monsoon and dry seasons. In addition, scatter plots were used to assess the relationships between rainfall and turbidity, as well as between water surface area and NDTI, reflecting the interactions between hydrological conditions and sediment transport processes. Linear regression trendlines were applied to the scatter plots to statistically evaluate both the strength and direction of these relationships. These visual and statistical analyses enabled the detection of distinct seasonal patterns, such as higher turbidity during the monsoon season and lower values during the dry season, providing essential insights for both scientific understanding and practical applications in water resource management.

3. Result

The results of this analysis, derived from Sentinel-2 MSI Level-2A surface reflectance data(COPERNICUS/S2_SR_HARMONIZED) covering the period from January 2019 to December 2024, are summarized in Table 1 and Figure 2. The NDTI was employed as a proxy for water turbidity, while the MNDWI was used to delineate water bodies and restrict calculations to water pixels. To incorporate hydrological context, monthly rainfall data from the TerraClimate dataset (IDAHO_EPSCOR/TERRACLIMATE) were integrated into the analysis. All datasets were processed and analyzed using the Google Earth Engine (GEE) platform.

Table 1. Annual mean values and variability of NDTI, rainfall, and water surface area in the Mekong River (2019–2024).

Year	NDTI (Mean ± SD)	Rainfall (mm) (Mean ± SD)	Water Area (km^2) (Mean ±SD)
2019	0.013 ± 0.07	858 ± 94.7	34.45 ± 13.4
2020	−0.004 ± 0.10	1318 ± 130.7	34.68 ± 9.3
2021	0.025± 0.10	1340 ± 90.4	36.99 ± 6.7
2022	0.05 ± 0.09	1567 ± 117.7	38.50 ± 7.2
2023	0.016 ± 0.09	1321 ± 126.6	36.82 ± 6.2
2024	0.039 ± 0.12	1978 ± 210.9	34.90 ± 11.9

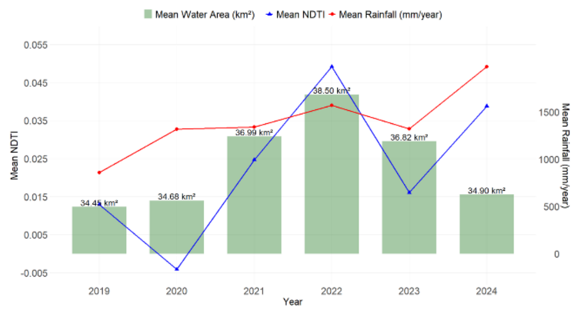
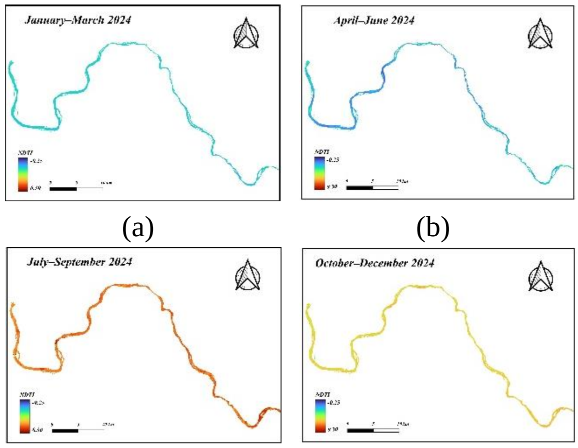


Figure 2 Annual Dynamics of Mean NDTI, Rainfall, and Surface Water Area in the Mekong River at Chiang Rai (2019–2024).

In addition, Figure 3 presents maps of the seasonal variation of turbidity (NDTI) in the Mekong River at Chiang Rai during 2024: (a) January-March, (b) April-June, (c) July-September, and (d) October-December.

3.1 Monthly NDTI Analysis

The analysis of the NDTI from January 2019 to December 2024 revealed distinct seasonal fluctuations in the Mekong River within Chiang Rai Province (Figure 4). NDTI values ranged from -0.18 to 0.20, reflecting increased turbidity during the monsoon season (June-September) and reduced turbidity during the dry season (November-April). The highest turbidity values were recorded in August 2020 and September 2024, when NDTI reached approximately 0.20, indicating elevated suspended sediment loads driven by rainfall and surface runoff. In contrast, the lowest values occurred in March-April 2020 and January-February 2024, with NDTI dropping below -0.15, signifying clearer water conditions during the dry season.



(a) (b) (c) (d)

Figure 3 Seasonal variation of turbidity (NDTI) in the Mekong River at Chiang Rai during 2024: (a) January-March, (b) April-June, (c) July-September, and (d) October-December.

This recurring annual cycle highlights the direct relationship between rainfall and turbidity: heavy rainfall leads to increased runoff and higher suspended sediment concentrations, raising NDTI values, while reduced rainfall corresponds to clearer water and lower NDTI values. These findings underscore the continuity of hydrological processes and the critical role of seasonal dynamics in shaping turbidity patterns in the Mekong River at Chiang Rai, as illustrated in Figure 3.

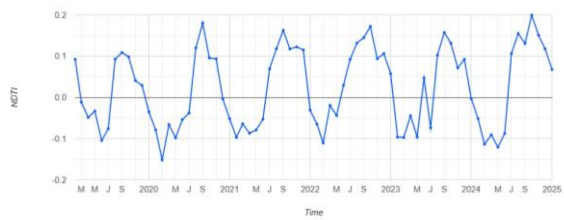


Figure 4 Monthly variation of the NDTI in the Mekong River at Chiang Rai (2019-2024).

3.2 Monthly Rainfall and NDTI Analysis

The time-series analysis of the NDTI and rainfall between January 2019 and December 2024 reveals a strong seasonal pattern in the Chiang Rai reach of the Mekong River (Figure 5). Peaks in rainfall during the monsoon months (June-September) consistently coincide with elevated NDTI values (up to ~0.20), indicating higher turbidity driven by increased runoff and suspended sediment inflows. Conversely, during the dry season (November-April), rainfall drops to near zero and NDTI values decline below -0.15, reflecting clearer water conditions.

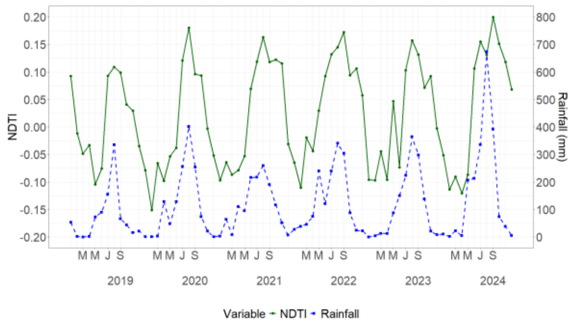


Figure 5 Monthly variation of rainfall and NDTI in the Mekong River at Chiang Rai (2019-2024).

3.3 Correlation Between Monthly Rainfall and NDTI

The relationship between monthly rainfall and turbidity, expressed by the NDTI, indicates a moderate positive correlation in the Chiang Rai reach of the Mekong River (Figure 6). The regression analysis yielded Equation (3).

$$NDTI = -0.0314 + 0.000412 \times Rain \quad (3)$$

Where NDTI = Normalized Difference Turbidity Index, a proxy for water turbidity.
Rain(mm) = Monthly rainfall in millimeters.

With a coefficient of determination of $R^2=0.37$ $(p<0.05)$ This suggests that approximately 37% of the variability in NDTI can be explained by monthly rainfall, as shown in Equation (3), This indicates a statistically significant but moderate linear relationship between precipitation and turbidity dynamics in the study area.

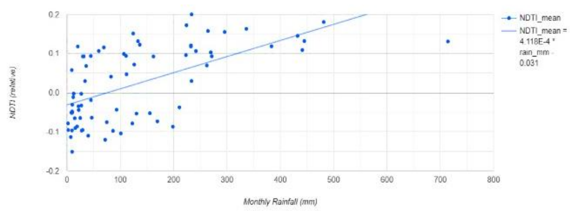


Figure 6 Scatter plot shows correlation between rainfall and NDTI in the Chiang Rai reach of the Mekong River.

3.4 Monthly Variability of NDTI and Water Area in the Mekong River

The analysis of monthly NDTI values and water surface area in the Chiang Rai reach of the Mekong River between 2019 and 2024 revealed clear seasonal dynamics (Figure 7). NDTI values tended to increase during the monsoon season (June-September), reflecting higher turbidity caused by increased sediment inflow, while lower values during the dry season (November-April) indicated clearer water conditions. In contrast, the water surface area remained relatively stable throughout most of the study period, showing only minor fluctuations.

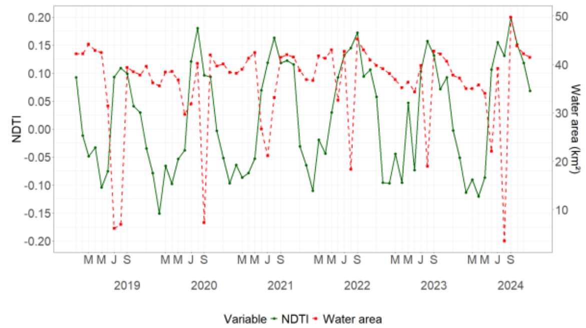


Figure 7 Monthly variation of NDTI and water surface area in the Chiang Rai reach of the Mekong River (2019-2024).

3.5 Correlation Between Water Area and NDTI

The relationship between water surface area and turbidity, expressed by the NDTI, shows a significant positive correlation in the Chiang Rai reach of the Mekong River (Figure 8). Linear regression analysis produced Equation (4), indicating that as the water surface area increases, the NDTI also tends to rise. This pattern reflects higher turbidity resulting from sediment resuspension and increased inflow during wetter hydrological conditions. The coefficient of determination $(R^2 = 0.514, p < 0.001)$ suggests that approximately 51% of the variability in NDTI can be explained by changes in water surface area.

$$NDTI = -0.863 + 0.022 \times Water\ Area \quad (4)$$

Where
NDTI = Normalized Difference Turbidity Index.
Water Area = Surface water area (km²).

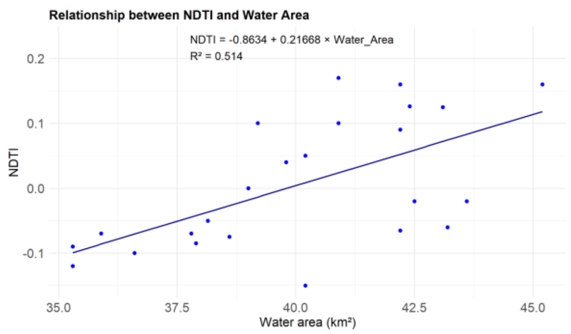


Figure 8 Scatter plot shows the relationship between water surface area and NDTI in the Chiang Rai reach of the Mekong River.

However, an important deviation from this trend occurs in September of every year, when the water surface area declines abruptly despite the river still being within the wet season. This anomaly is not attributable to reduced rainfall but instead reflects upstream hydropower flow regulation from dams in China and Laos, which typically begin storing water in preparation for the dry season. As a result, turbidity levels (NDTI) remain relatively high due to sediment mobilization from preceding monsoon flows, while the observable surface water area decreases sharply. This decoupling effect creates outlier behavior in the regression model and slightly reduces the overall coefficient of determination.

4. Discussion

The analysis of turbidity dynamics in the Mekong River at Chiang Rai provides valuable insights into the seasonal variability and hydrological drivers of water quality. Spatial and temporal analysis of the NDTI revealed a clear seasonal cycle, with elevated turbidity during the monsoon (June-September) and reduced turbidity in the dry season (November-April). Peak NDTI values (~0.20) in August 2020 and September 2024 coincided with heavy rainfall and surface runoff, while the lowest values (< -0.15) were recorded during dry months such as March-April 2020 and January-February 2024. These findings support the hypothesis that turbidity in the Chiang Rai reach is strongly influenced by seasonal precipitation regimes, consistent with studies in other dynamic river systems, such as the Godavari River [5] and the Panchet Dam [4], where turbidity patterns were closely linked to rainfall and seasonal hydrological conditions.

The spatio-temporal analysis of turbidity in the Chiang Rai reach revealed a clear monsoonal pattern, with elevated NDTI values during June-September and reduced turbidity in the dry season, reflecting strong seasonal hydrological control. However, the statistical analysis demonstrates that rainfall alone is not the dominant driver of turbidity dynamics. Although the rainfall-NDTI relationship was significant (R^2 = 0.37), the moderate strength of this correlation indicates that precipitation acts only as an indirect trigger of sediment processes. Similar decoupling between rainfall and turbidity has been observed in other large river basins, such as Chao Lake, China [7], where long-term increases in turbidity were driven more by sediment resuspension and land disturbance than by rainfall intensity.

In contrast, the stronger correlation between water surface area and turbidity (R^2 = 0.514) suggests that hydromorphological expansion of the river corridor is a more direct proxy for sediment mobilization. When the wetted width increases, flow energy and shear stress rise, enhancing bank erosion, sediment resuspension, and channel-bar scouring. This explains why turbidity can remain high even after rainfall decreases, and why floodplain connectivity plays a key role in sediment delivery. It also clarifies the “September anomaly,” in which river width drops sharply while turbidity remains elevated-an indicator of upstream hydropower storage operations in China and Laos, which reduce surface extent but continue releasing sediment-rich flows. Similar regulation-driven decoupling has been documented in the Yangtze and Lancang-Mekong mainstream.

While NDTI proved effective for detecting seasonal turbidity patterns, several limitations must be acknowledged. First, NDTI is an optical proxy and does not directly measure suspended sediment concentration (SSC), meaning its spectral sensitivity may vary with sediment type, grain size, and water color. Second, the absence of field-measured turbidity or SSC data in this study prevents full quantitative validation of satellite retrievals. Third, the reported correlations fall within a moderate range ($R^2 < 0.6$), indicating that predictive applications of NDTI alone may be inadequate without incorporating additional drivers such as discharge, dam-release data, and watershed land use.

Alternative spectral indices may offer improved performance. Previous work in the Mekong River indicated that the Normalized Difference Suspended Sediment Index (NDSSI) produced higher accuracy than NDTI for SSC estimation[3],while red-edge-based turbidity models using Sentinel-2 band 5 achieved superior performance in highly dynamic rivers such as the Godavari [4,5]. Future work should therefore compare NDTI with red-edge and SWIR-based algorithms or apply machine-learning regression using multi-band spectral inputs combined with hydrological variables.

Overall, this study provides the first satellite-based turbidity assessment for the Chiang Rai reach and demonstrates the practical value of integrating Sentinel-2 monitoring into basin-wide water-quality systems, particularly where in-situ networks are sparse. A combined satellite and field-based validation framework would enhance the capacity of the Mekong River Commission and national agencies to detect sediment anomalies, assess hydropower impacts, and strengthen early-warning and sediment-management strategies across the transboundary Mekong Basin.

5. Conclusion

This study applied the NDTI derived from Sentinel-2 MSI data to examine the spatial and seasonal dynamics of turbidity in the Mekong River at Chiang Rai, a critical upstream reach of the Lower Mekong Basin. The findings highlight several key insights.

First, consistent with the study hypothesis, turbidity exhibited a clear seasonal cycle, with elevated NDTI values during the monsoon season (June-September) and reduced values during the dry season (November-April). This pattern reflects the dominant role of rainfall-driven processes in controlling suspended sediment transport. Second, the analysis confirmed a moderate positive correlation between rainfall and NDTI ($R^2 = 0.37$), indicating that precipitation is an important, though not exclusive, driver of turbidity dynamics. Additional hydrological and geomorphological processes-such as sediment resuspension, bank erosion, and floodplain connectivity-also play a significant role in shaping turbidity levels. Third, the relationship between water surface area and turbidity showed a stronger positive correlation ($R^2 = 0.514$), underscoring that riverine hydro morphological factors exert a more direct influence on turbidity than rainfall alone.

Integrating these results, the study demonstrates the practical value of Sentine l-2 based NDTI as a cost-effective tool for monitoring turbidity in large, dynamic river systems. Compared with conventional field-based networks, which are often limited in coverage, unevenly distributed, and costly to maintain, satellite observations provide high-resolution, frequent, and spatially consistent data. The findings confirm that NDTI remains a reliable proxy for monitoring seasonal and hydrological turbidity dynamics, particularly in data-scarce regions such as Chiang Rai.

However, several limitations should be acknowledged. (1) NDTI is used as a single proxy index for turbidity and does not directly measure suspended sediment concentration (SSC), meaning its accuracy may vary with optical conditions, sediment characteristics, or concentration saturation. (2) The study lacks field-based turbidity or SSC validation data, which prevents full assessment of the absolute accuracy of satellite-derived values. (3) The statistical relationships observed ($R^2 = 0.37$ and 0.514) indicate moderate not strong correlation levels, suggesting that turbidity cannot be fully explained by rainfall or water area alone and may require additional hydrological inputs such as discharge or dam-release data.

In summary, this research advances current understanding by addressing the gap in turbidity monitoring for the Chiang Rai reach of the Mekong River, an upstream area of strategic importance to the Lower Mekong Basin that has not been systematically studied. The results reinforce the importance of integrating satellite-derived indices into basin-wide and transboundary water quality monitoring frameworks. Such approaches can complement field observations, provide timely and spatially extensive information, and support sustainable water resource management in the Mekong region under the combined pressures of climate change and human activities.

Although this study has demonstrated the potential of using the NDTI derived from Sentinel -2 data for monitoring turbidity in the Mekong River at Chiang Rai, several avenues for future research remain. First, integrating data from higher-frequency satellite missions (e.g., Sentinel -1 SAR or Planet Scope imagery) could enhance the temporal resolution of turbidity monitoring, particularly during rapid hydrological events such as flash floods. Second, linking remote sensing data with hydrodynamic and sediment transport models would enable predictive assessments of turbidity under future climate change and land-use scenarios, thereby strengthening the capacity for proactive water resource management.

Third, future work should compare NDTI with alternative turbidity indices (e.g., NDSSI, red-edge indices) and incorporate field validation campaigns to improve reliability of satellite-based monitoring.

6. Acknowledgment

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