Assessment of Suspended Sediment Concentration in the Mekong River Using Landsat-8 Data

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Abstract. *The Mekong River is a vital waterway in Southeast Asia, significantly impacted by sediment dynamics driven by both natural factors and human activities. This research aims to address knowledge gaps in the application of remote sensing for sediment monitoring by evaluating the effectiveness of three indices: the Normalized Difference Suspended Sediment Index (NDSSI), the Normalized Suspended Material Index (NSMI), and the Normalized Difference Turbidity Index (NDTI) in estimating Suspended Sediment Concentration (SSC) in the section of the Mekong River flowing through Thailand. Landsat-8 satellite imagery, validated with field data collected from 2017 to 2023, was utilized in this study. The findings identified NDSSI as the most accurate index, with an* R^2 *of 0.723 and an RMSE of 20.2 mg/L. Comparatively, NSMI showed moderate performance (*$R^2 = 0.512$*, RMSE = 25.8 mg/L), while NDTI exhibited the lowest accuracy (*$R^2 = 0.418$*, RMSE = 27.5 mg/L). The study indicates that NDSSI is the most suitable tool for sediment monitoring in highly turbid river systems, whereas NSMI and NDTI require further refinement to enhance their applicability in complex hydrological environments. This research highlights the significant potential of remote sensing for sustainable sediment management, offering actionable insights to improve monitoring methods and supporting future work in integrating advanced modeling techniques with high-resolution satellite data to effectively address sediment-related challenges.*

Keywords:

Mekong River, Suspended Sediment Concentration (SSC), Remote Sensing, Landsat-8, Normalized Differential Suspended Sediment Index (NDSSI)

1. Introduction

The Mekong River, originating from the Tibetan Plateau in China, flows through six countries: China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. Stretching about 4,909 kilometers, it forms a natural border between Thailand and Laos for 1,520 kilometers, spanning seven Thai provinces: Chiang Rai, Loei, Nong Khai, Bueng Kan, Nakhon Phanom, Mukdahan, and Ubon Ratchathani [1]. The river is vital to Thailand’s economy and livelihoods, providing water for agriculture, fisheries, and serving as an international trade route, boosting income and quality of life for local communities.

The Mekong River faces challenges such as seasonal sediment flow variations, high sediment loads, and the impacts of human activities like dam construction and land-use changes. These factors create complex hydrological and sedimentary environments, significantly affecting the river's ecosystem. Key issues include riverbank erosion, sediment accumulation in agricultural areas, and a decline in aquatic life [2]. Studying sediment dynamics across seasons is key to understanding nutrient transport, supporting biodiversity, and preserving fertile floodplains critical for agriculture and the economy. Continuous monitoring of sediment changes in the Mekong River is vital for sustainable water management policies, ensuring its long-term importance for Thailand's people and economy.

Suspended Sediment Concentration (SSC) measures the sediment, including soil, sand, and organic particles, suspended in water. It is crucial for assessing water quality and environmental dynamics, as SSC carries pollutants and affects processes like photosynthesis by altering water clarity [3]. Monitoring SSC helps address erosion, sediment deposition, and river morphology changes, especially in major rivers essential for agriculture, fisheries, and transportation. Infrastructure developments like dams significantly impact SSC, affecting sediment transport and ecosystem health in the region [4], [5].

Traditional field methods for monitoring SSC, while effective, have limitations in scope, frequency, and accuracy, particularly in large and complex systems, posing challenges to efficient sediment management. Satellite remote sensing has emerged as a promising alternative for evaluating sediment dynamics. Advances in satellite imagery have significantly enhanced SSC monitoring in major rivers, providing valuable insights into sediment behavior and water quality. High-resolution sensors improve spatial and temporal observation capabilities, enabling more accurate analyses of sediment concentration and distribution [6], [7], [8].

The monitoring of suspended sediment concentrations (SSC) in rivers has been significantly advanced through the development and application of various satellite-derived indices. Key indices include the Normalized Difference Suspended Sediment Index (NDSSI), which uses red and near-infrared (NIR) reflectance to effectively assess SSC in turbid waters [9], [10], [11], [12], [13], and the Normalized Suspended Matter Index (NSMI), which combines NIR and shortwave infrared (SWIR) bands to evaluate suspended particulates [10], [14], [15], [16], [17]. Other critical tools include the Normalized Difference Turbidity Index (NDTI), designed for assessing turbidity using red and green reflectanc [10], [18], [19], [20], and Reflectance Ratios, which utilize band-specific calculations to distinguish clear and turbid water [21]. Advanced indices like Enhanced Water Index (EWI) and Turbidity Reflectance Index (WTRI) address dynamic SSC changes across temporal and spatial scales [22]. Techniques such as Band Ratio Analysis, Multispectral Band Analysis, and Depth-Integrated Reflectance Models further improve SSC monitoring accuracy, particularly in complex riverine systems [23], [24].

Research on estimating suspended sediment concentration (SSC) using satellite-derived indices like NDSSI, NSMI, and NDTI has showcased the efficiency of diverse approaches in analyzing sediment dynamics across a wide range of environments. The Normalized Difference Suspended Sediment Index (NDSSI), introduced by Hossain et al. [11] using Landsat 7 ETM+ data, measures surface reflectance to assess water clarity and estimate suspended sediment concentrations (SSC). It utilizes the blue band, which has the highest reflectance, and the near-infrared (NIR) band, which has the lowest reflectance for water, calculated as the difference between these bands divided by their sum. For Sentinel-2 data, NDSSI uses bands 2 (Blue: 0.458–0.523 μm) and 8 (NIR: 0.785–0.899 μm) [12], with values ranging from −1 (highest SSC) to +1 (lowest SSC). NDSSI supports large-scale, non-invasive monitoring of water quality and turbidity but requires atmospheric correction and in-situ calibration for accuracy. Its effectiveness has been demonstrated in the Indus Delta, where it achieved an R^2 of 0.88 and RMSE of 67.24 mg/L [10], proving valuable for sediment management and environmental studies. The Normalized Suspended Material Index (NSMI) is a robust tool for estimating suspended sediment concentrations (SSC) in water, designed to monitor diurnal SSC variability and assess water quality. Introduced by Montalvo et al. [15], it utilizes the reflectance peak in the blue band and increased reflectance in the green and red bands caused by suspended sediments. The NSMI is calculated by summing the red and green bands, subtracting the blue band, and dividing by the total of all three bands, yielding values from −1 to +1, where low values indicate clear water and high values reflect greater sediment presence [16], [17]. The index can also use shortwave infrared (SWIR) and green bands for broader applications, integrating effectively with indices like the Normalized Difference Turbidity Index (NDTI). Case studies highlight its effectiveness, such as in the Arabian Gulf (NSMI: 0.012–0.430; R^2 = 0.95) [10] and the Mekong Delta (R^2 = 0.92 for TSS) [14], confirming its reliability for sediment monitoring and environmental studies. The Normalized Difference Turbidity Index (NDTI), introduced by Lacaux et al. [19], is a reliable tool for turbidity and suspended sediment concentration (SSC) mapping, particularly in coastal and estuarine environments. It utilizes the reflectance difference between red and green bands, where red band reflectance increases with turbidity while green band reflectance remains weak [10]. NDTI values range from −0.2 to +0.25, with lower values indicating clear water and higher values representing turbid conditions [20]. The index effectively identifies turbid water and estimates SSC, given the linear relationship between turbidity and SSC. In practical applications, NDTI has demonstrated its utility, such as in the Arabian Gulf (values: −0.44 to 0.12, R^2 = 0.95 with NSMI) [10] and in Lake Nokoue (values: −0.045 to 0.0723), where it successfully mapped pollution patterns [18]. Despite requiring in-situ calibration and atmospheric corrections, NDTI remains a sensitive and easy-to-use index for sediment monitoring and water quality assessment.

Research on suspended sediment concentration (SSC) in the Mekong River highlights that remote sensing has become an essential tool for monitoring SSC and gaining insights into sediment dynamics in large river systems. A study on the Mekong floodplains utilized Landsat TM/ETM+ data with Principal Component Analysis (PCA) to quantify SSC, achieving coefficients of determination (R^2) between 0.66 and 0.92. The study highlighted sediment dynamics at critical confluences, such as Chaktomuk in Cambodia, and discussed the impact of flood prevention systems on sediment supplies to the delta [25]. Another research effort in the Mekong Delta demonstrated the integration of in situ SSC measurements and multi-spectral remote sensing imagery to develop empirical models for spatial SSC mapping. These models achieved an RMSE of 0.038 g/L, and a decadal analysis revealed a 1% annual decrease in SSC since 2001, correlating sediment trends with hydrological changes [26]. In Vietnam’s Red River, Landsat-8 images were employed alongside in situ measurements to establish a band-ratio method (green/red), yielding an R^2 of 0.75 and an RMSE of ~0.3 mg/L. Seasonal analysis indicated that SSC during the rainy season was nearly double that of the dry season, driven by variations in runoff [27]. In the Hau River within the Mekong Delta, Sentinel-2A data and the Normalized Suspended Material Index (NSMI) were applied to map total suspended solids (TSS), achieving an R^2 of 0.92. Results showed that suspended material concentrations were higher in areas without dyke protection, emphasizing the role of dykes in sediment dynamics [14]. A broader study on the Mekong River Basin utilized Landsat imagery and the RUSLE model to integrate soil erosion (SE) and sediment load (SSL) assessments. It found significant seasonal SSC variations, with R^2 values of 0.87 for NIR-band-based models [28]. Finally, historical analysis of the Lancang-Mekong River basin from 1968 to 2002 revealed that land cover changes surpassed rainfall as the dominant factor influencing SSC after the 1980s. This study introduced a sediment deposition index to refine regional sediment composition estimates, emphasizing the interplay between anthropogenic and natural factors in sediment dynamics [29].

Although satellite-derived indices have been widely used to estimate suspended sediment concentrations (SSC) in various aquatic ecosystems, challenges remain in identifying the most effective indices for analyzing SSC dynamics in complex riverine environments. The Mekong River Basin is characterized by dynamic hydrological systems, including seasonal flooding, sediment-laden waters, and human-induced impacts. Various research reports [9], [10], [14], [16], [18], [19] highlight the potential of indices such as NDSSI, NSMI, and NDTI due to their specific spectral configurations. However, the effectiveness of these indices in addressing the unique sedimentary and hydrological conditions of the Mekong River has yet to be thoroughly investigated.

This study evaluates the applicability of NDSSI, NSMI, and NDTI in the Thai section of the Mekong River. Data from nine monitoring stations, representing varied hydrological conditions, form a robust dataset for analysis. These indices were selected for their ability to address the Mekong's specific sediment and hydrological characteristics more effectively than generalized indices, aiming for precise SSC mapping.

The relationship between spectral reflectance from NDSSI, NSMI, and NDTI indices derived from Landsat 8 imagery and SSC was analyzed using Linear Regression, with model performance evaluated using R^2 and RMSE. Linear Regression was chosen for its simplicity and clarity, aligning with the study's goal of understanding and quantifying the direct link between the indices and SSC, while providing insights into each spectral band's contribution.

2. Study Arae

The Mekong River is one of the largest rivers in Southeast Asia [30]. It originates from the melting of ice and snow on the Tibetan Plateau in Tibet and China. which flows through the border between Thailand and Lao PDR through Chiang Rai, Nong Khai, Bueng Kan, Nakhon Phanom, Mukdahan, Amnat Charoen and Ubon Ratchathani, a distance of 1,520 kilometers, then flows into Lao PDR. Figure 1. The main characteristics of the Mekong River are There are very steep banks on both sides. flowing along the mountainside There is a stream flowing from north to south throughout the year. During the flood season This topography has resulted in many islands along the Mekong River. Especially in areas where the Mekong River flows through the northeastern region of Thailand. Caused by the accumulation of sediment and water erosion. Average temperatures range from 25°C to 40°C. Water levels vary greatly in the wet and dry seasons. Average rainfall ranges from 1,200 to 2,000 millimeters per year. The speed of the current depends on the season. The soil in the Mekong River is sandy. There are over a hundred large and small islands lined up along the river. The Mekong River flows through many countries. Covers the basin's catchment area of 795,000 square kilometers. As a result, natural resources are diverse and abundant. It is a source of water for consumption, agriculture, industry and fishing.

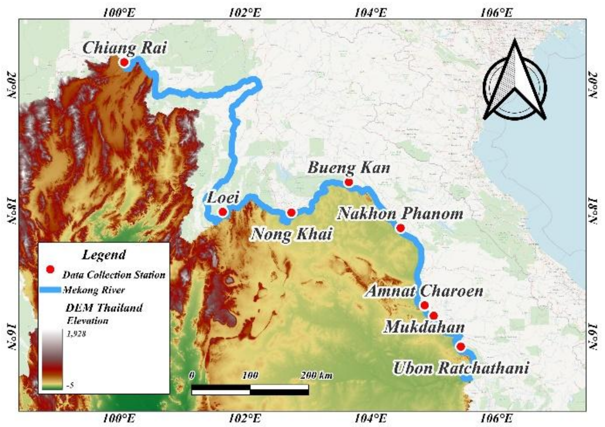

Fig. 1 The Mekong River route in Thailand

3. Methods

To assess the suspended sediment concentration (SSC) in the Mekong River using Landsat-8 data, the process begins with acquiring the relevant satellite imagery and any necessary ancillary data, such as in-situ SSC measurements for validation. The data undergoes preprocessing steps, including radiometric and atmospheric corrections, geometric alignment, and cloud masking, to ensure accurate analysis. Once preprocessed, specific Landsat-8 bands sensitive to sediment concentrations are selected, and algorithms are applied to estimate SSC. The analysis involves evaluating spatial and temporal patterns in SSC across the river, followed by validating the results against ground-truth data to ensure accuracy. A process flow diagram for the assessment of SSC in the Mekong River using Landsat-8 data can be seen in Figure 2.

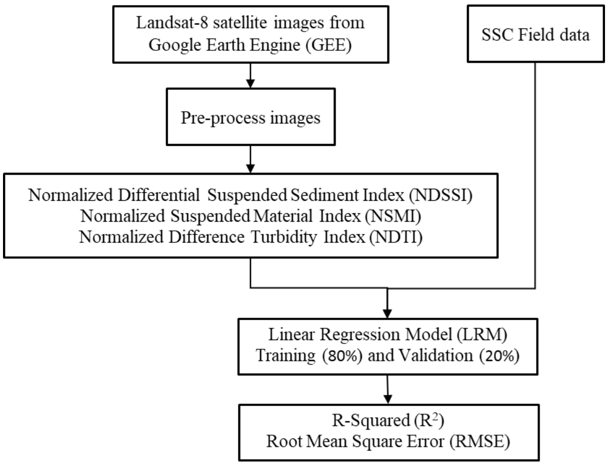

Fig. 2 Process Flow Diagram for Assessment of SSC in the Mekong River Using Landsat-8 Data

A. Satellite Data

In this study, we used data from the Landsat 8 Operational Land Imager (OLI) to cover the study area up until 2023. The Landsat 8 images were pre-processed to correct for atmospheric effects such as smog and cloud-covered areas. Landsat 8 OLI comprises nine spectral bands: coastal (443 nm), blue (485 nm), green (563 nm), red (655 nm), panchromatic (640 nm), near-infrared (NIR) (865 nm), short-wave infrared 1 (SWIR1) (1610 nm), SWIR2 (2200 nm), and cirrus (1375 nm). The selected satellite images had a cloud cover of no more than 10% (source; accessed on December 25, 2023).

Spectral indices are numerical values derived from the spectral properties of remote sensing data, typically acquired from satellites. These indices involve mathematical transformations utilizing two or more wavelengths to enhance the information contained in the data. They serve to quantify various biophysical and biochemical properties of the Earth's surface, such as vegetation health, water content, and soil characteristics. In this study, we utilized several spectral indices, including NDSSI, NSMI, and NDTI, derived from Landsat 8 data. Multiple images covering the entire research period were employed, and spectral indices were computed using Google Earth Engine (GEE).

B. Field Information

This study utilized field data from the Mekong River Commission (MRC) on suspended sediment concentration (SSC) collected from water monitoring stations along the Mekong River in Thailand. The data, spanning from 2017 to 2023, aimed to enhance understanding of sediment dynamics, crucial for managing water resources and maintaining ecological balance. A total of 315 samples were collected from nine strategically selected monitoring stations, ensuring a comprehensive analysis of sediment loads. Each station contributed 35 samples, covering both dry and wet seasons, to capture seasonal variations in sediment concentration. These samples were used for training and validation, enabling the development of accurate models for predicting SSC.

C. Index Calculation

The Normalized Difference Suspended Sediment Index (NDSSI), the Normalized Suspended Material Index (NSMI), and the Normalized Difference Turbidity Index (NDTI) are vital tools for monitoring and assessing environmental conditions, with a particular focus on suspended sediments and materials. By utilizing data from satellite imagery, these indices provide critical insights into water quality, sediment behavior, and land-use dynamics, playing a key role in managing and understanding environmental changes. Grounded in the spectral reflectance properties of water bodies and suspended sediments, as captured through remote sensing, these indices are derived using the normalized difference principle. This principle highlights variations in reflectance while minimizing the effects of atmospheric interference and lighting conditions, making these indices highly effective for a wide range of environmental applications.

The Normalized Difference Suspended Sediment Index (NDSSI) utilizes the spectral contrast between Near-Infrared (NIR) and Short-Wave Infrared (SWIR) bands to identify suspended sediments [10]. Suspended sediments exhibit higher reflectance in the NIR band and lower reflectance in the SWIR band, making this contrast ideal for detection. The formula for NDSSI is presented in Table 1. This index is derived using the normalized difference principle, which enhances reflectance differences while mitigating the influence of atmospheric and illumination variations. NDSSI is particularly effective for detecting suspended sediments in highly turbid waters and regions with significant sediment loads, providing a robust tool for water quality and sediment analysis.

The Normalized Suspended Materials Index (NSMI) leverages the reflectance properties of water and suspended sediments, focusing on the Red and Near-Infrared (NIR) spectral bands [10]. The formula for NSMI is presented in Table 1. The Red band is particularly sensitive to chlorophyll absorption and sediment, while the NIR band captures the scattering of sediments. Using the normalized difference principle, the NSMI formula emphasizes reflectance differences to detect the presence of suspended sediments. This index is especially effective in shallow waters with moderate turbidity, providing a reliable tool for analyzing suspended materials and water quality.

The Normalized Difference Turbidity Index (NDTI) quantifies water turbidity by utilizing the contrast between the Green and Red spectral bands [10]. The formula for NDTI is provided in Table 1. These bands capture the optical properties of water and suspended particles, with the Green band being more sensitive to suspended sediments and the Red band influenced by chlorophyll absorption and organic matter. By applying the normalized difference principle, NDTI enhances sensitivity to turbidity variations, making it a robust tool for assessing water clarity and turbidity levels. It is widely used for monitoring rivers, lakes, and coastal regions to evaluate sediment dispersion and water quality.

In this study, Landsat-8 imagery was processed to compute the NDSSI, NSMI, and NDTI values, providing a detailed spatial and temporal representation of the study area. These indices are advantageous due to their sensitivity to suspended materials and turbidity, allowing for the identification of regions with high sediment concentrations or areas impacted by land-use activities such as deforestation or urbanization. NDSSI leverages red and near-infrared (NIR) bands to detect suspended sediments in highly turbid waters, demonstrating its effectiveness in areas with varying turbidity and substantial sediment loads [9]. NSMI combines NIR and shortwave infrared (SWIR) bands, offering increased sensitivity to suspended particles and efficiently distinguishing sediments from other water components, especially in regions affected by monsoonal conditions [14]. Meanwhile, NDTI employs red and green bands to accurately capture turbidity variations [10], supporting the monitoring of sediment dispersion over time.

Table 1 Index used to identify suspended sediment in this study.

No	Index	Formula	Ref
1	NDSSI	$\frac{Blue\ -\ NIR}{Blue\ +\ NIR}$	[10]
2	NSMI	$\frac{Red + Green - Blue}{Red + Green + Blue}$	[10]
3	NDTI	$\frac{(Red - Green)}{(Red + Geen)}$	[10]

Where Blue, Green, and Red are the visible wavelengths of blue, green, and red light, represented by Bands 2, 3, and 4, respectively, and NIR is the near-infrared wavelength, represented by Band 5 on Landsat-8.

D. Data Processing and Data Analysis

The NDSSI, NSMI, and NDTI indices were validated by comparing predicted suspended sediment concentration (SSC) values with actual field measurements to assess the accuracy and reliability of the Linear Regression Model (LRM). The dataset was divided into training (80%) and validation (20%) subsets to ensure a balanced and robust model development process. The training dataset was used to calibrate the LRM, using NDSSI, NSMI, and NDTI as input variables to predict environmental parameters such as sediment concentration and turbidity. The validation dataset tested the model’s predictive performance using two statistical metrics: R-Squared (R^2) and Root Mean Square Error (RMSE), defined in Equations (1) and (2), respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2} \quad (2)$$

Where:

N: Total number of data points.

y_i: Observed SSC value from field measurements for the i^{th} sample.

$\hat{y}_i$: *Predicted SSC value from the model for the* i^{th} *sample.*

$\bar{y}$: *Mean of observed SSC values.*

The R^2 value indicates the proportion of variance in the observed data explained by the model, reflecting how well predictions align with actual measurements, while RMSE quantifies the average magnitude of prediction errors. Higher R^2 values and lower RMSE values signify better model performance. The validated indices were then used to map SSC across the study area, enabling a detailed analysis of sediment dynamics and distribution. The process for assessing SSC in the Mekong River using Landsat-8 data is outlined in Figure 2: Process Flow Diagram for Assessment of SSC in the Mekong River Using Landsat-8 Data, which illustrates the steps from data preprocessing, index calculation, model validation, and SSC mapping. This systematic approach ensures reliable results, providing actionable insights for environmental monitoring and management.

4. Results

Analyze the relationship between in-situ suspended sediment concentration and reflectance values from Landsat-8 data to develop a model for estimating suspended sediment values. The relationship is illustrated in Figure 3.

This study evaluates the performance of three remote sensing indices: normalized differential suspended sediment index (NDSSI), normalized suspended material index (NSMI), and The Normalized Difference Vegetation Index (NDTI) to suspended sediment concentration (SSC) in the Mekong River assessment using Landsat-8 data Training and validation within situ measurements.

The performance of the three indices (NDSSI, NSMI, and NDTI) was evaluated using both R-square and RMSE metrics for training and validation datasets. The summarized results are as follows:

NDSSI demonstrated the best performance among the three indices. It achieved the highest R-square values (0.756 for training and 0.723 for validation), indicating a better fit for the model. Additionally, it had the lowest RMSE values (18.3 for training and 20.2 for validation), suggesting the least prediction error.

NSMI showed moderate performance with R-square values of 0.615 (training) and 0.512 (validation), and RMSE values of 24.2 (training) and 25.8 (validation). This indicates that while NSMI performs reasonably well, it is not as accurate as NDSSI.

NDTI had the lowest performance, with R-square values of 0.450 (training) and 0.418 (validation), and RMSE values of 26.8 (training) and 27.5 (validation). These results suggest that NDTI is the least reliable index for this dataset, indicating limited reliability in accurately estimating SSC compared to other indices.

The results, including the R^2 and RMSE values of the linear regression model, are summarized in Table 2. Figure 4 presents a scatter plot showing the relationship between predicted suspended sediment concentration from Landsat-8 data and observed suspended sediment concentration, based on three indices used in this study. Figure 5 displays SSC maps for April (dry season) and September (rainy season) of 1985, 2015, and 2023, estimated from the linear regression model.

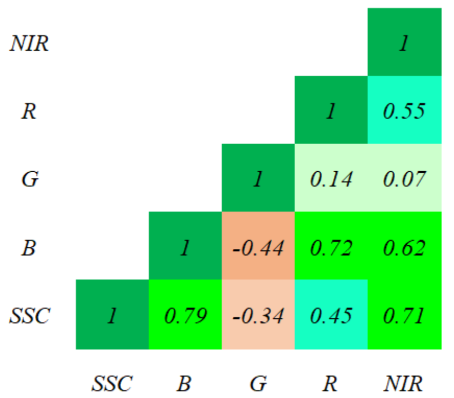

Fig. 3 Correlation between Landsat-8 data reflectance and in-situ SSC.

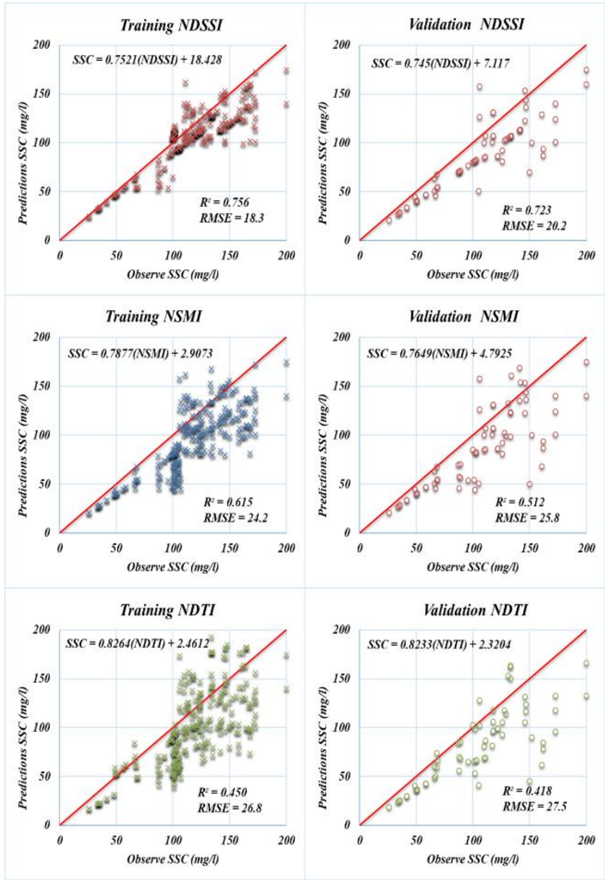

Fig. 4 Scatter plot illustrating the relationship between predicted and observed SSC, based on Landsat-8 measurements using three indices.

Table 2 R^2 Value and RMSE Value of Linear regression model indicated $P < 0.01$.

No	Index	Training		Validation	
		R^2	RMSE	R^2	RMSE
1	NDSSI	0.756	18.3	0.723	20.2
2	NSMI	0.615	24.2	0.512	25.8
3	NDTI	0.450	26.8	0.418	27.5

5. Discussion

The Normalized Difference Suspended Sediment Index (NDSSI) demonstrated exceptional reliability for estimating suspended sediment concentration (SSC), achieving an R^2 value of 0.723 and a Root Mean Square Error (RMSE) of 20.2 mg/L during validation. These results align with findings from studies in other highly turbid environments. For instance, Shahzad et al. [9] validated NDSSI in the Indus Delta Region, achieving a high coefficient of determination (R^2 = 0.88) and a low RMSE of 67.24 mg/L, highlighting its ability to capture spatial variability in highly turbid waters. Similarly, Sankaran et al. [10] demonstrated NDSSI's strong correlation (R^2 = 0.95) with in-situ measurements in the Arabian Gulf, emphasizing its suitability for sediment monitoring in arid marine environments. In riverine contexts, Hossain et al. [11] utilized NDSSI to monitor SSC during extreme hydrological events in the Mississippi River, while Kavan et al. [12] employed the index to track sediment fluxes from glacial lakes to fjords in Svalbard, demonstrating its effectiveness in monitoring sediment dynamics.

NDSSI utilizes the red and near-infrared (NIR) spectral bands, which are highly sensitive to suspended sediment reflectance. The red band captures the reflectance of sediment particles, while the NIR band minimizes water reflectance, enabling precise differentiation between sediment-laden and clear waters. NDSSI's strong performance is attributed to its ability to provide consistent and reliable data across spatial and temporal scales. Various studies have highlighted NDSSI's applicability in diverse environments, such as the Indus Delta Region, the Arabian Gulf, the Mississippi River, and glacial lakes, achieving high predictive accuracy for SSC [9], [10], [11], [12]. With these capabilities, NDSSI is particularly well-suited for monitoring and managing sediment dynamics in the Mekong River, which is characterized by high sediment loads.

The Normalized Suspended Material Index (NSMI) demonstrated moderate performance during validation, with an R^2 value of 0.512 and a Root Mean Square Error (RMSE) of 25.8 mg/L. While these metrics indicate its utility for suspended sediment concentration (SSC) estimation, the results suggest room for improvement, particularly when compared to other indices such as the Normalized Difference Suspended Sediment Index (NDSSI), which has shown higher predictive accuracy in similar studies. For instance, Nguyen and Phan [14] achieved R^2 values exceeding 0.7 in their work on sediment distribution mapping in the Hau River, highlighting the potential of alternative methods and indices in capturing more nuanced sediment patterns. In more stable and less dynamic environments, NSMI has shown promise, as reported by Montalvo [15], who documented an R^2 of 0.65 and an RMSE of 18 mg/L in coastal sediment monitoring. However, applying NSMI in highly variable sedimentary systems, such as the Barito Delta, poses significant challenges. [17] noted that SSC in such regions can fluctuate by more than 30 mg/L within a single tidal cycle, which complicates the index's performance without precise calibration. Addressing these challenges requires leveraging advanced methodologies, including the use of additional spectral bands and higher-resolution satellite imagery. Sankaran et al. [10], for example, reported a 15% reduction in RMSE, achieving 22 mg/L and an R^2 of 0.61 by utilizing Sentinel-2's full spectral range, demonstrating the value of such enhancements in arid and complex environments. By integrating these improvements and tailoring calibration to specific environmental conditions, NSMI's predictive accuracy can be significantly enhanced, enabling more robust sediment monitoring in diverse and challenging systems.

The Normalized Difference Turbidity Index (NDTI) demonstrated the weakest performance, with an R^2 of 0.418 and an RMSE of 27.5. Designed primarily for turbidity assessment, NDTI relies on the red and green spectral bands, which are less effective for detecting suspended sediment concentration (SSC) in sediment-rich waters. This limitation is evident in the Mekong River context, contrasting with its better performance in other environments. For instance, Dabire et al [18]. achieved an R^2 of 0.72 and an RMSE of 15.3 in mapping turbidity in less sediment-dense conditions [18]. Despite its lower accuracy in sediment-heavy scenarios, NDTI retains value in clearer or less dynamic water systems. Its potential for SSC estimation could be enhanced by integrating additional indices or spectral bands, as demonstrated by Sankaran et al. through the application of Sentinel-2 data and advanced indices [10], [19].

The performance of these indices in the Mekong River reflects trends observed in global studies. The Normalized Difference Suspended Sediment Index (NDSSI) consistently demonstrates superior accuracy in turbid environments due to its heightened spectral sensitivity to sediment reflectance [9], [10]. In contrast, the Normalized Suspended Material Index (NSMI) shows promising results in more stable environments, such as coastal and less dynamic systems, emphasizing its potential for context-specific applications [15], [17]. On the other hand, the Normalized Difference Turbidity Index (NDTI) exhibits limitations in sediment-heavy systems like the Mekong River, underlining the critical need for tailoring indices to align with specific environmental and hydrological conditions [10], [19].

Despite the promising results, several limitations hinder the full potential of satellite-derived SSC monitoring. The 16-day revisit interval and 30 meter spatial resolution of Landsat-8 restrict its ability to capture rapid or localized changes in SSC, making higher-resolution platforms like Sentinel-2, with its 5 day revisit cycle, more suitable for achieving finer spatial and temporal granularity [12], [14], [17], [21]. Atmospheric interference, such as haze, clouds, and scattering, introduces noise into satellite measurements, reducing accuracy, while mixed pixels representing multiple surface types within a single pixel further complicate the extraction of pure SSC signals [6], [10]. Additionally, variability in water properties, including turbidity, color, and dissolved organic matter, impacts spectral reflectance, presenting challenges for consistent SSC estimation, particularly for indices like NSMI and NDTI used in this study [15], [20], [21]. Furthermore, linear regression models used in this study cannot capture non-linear relationships, highlighting the need for advanced modeling techniques to improve accuracy[8], [17], [20].

The strong performance of NDSSI underscores its reliability as a tool for SSC monitoring in sediment-rich environments like the Mekong. Its ability to capture sediment dynamics across temporal and spatial scales makes it a valuable resource for sustainable sediment management. Conversely, the moderate-to-weak performance of NSMI and NDTI suggests that further

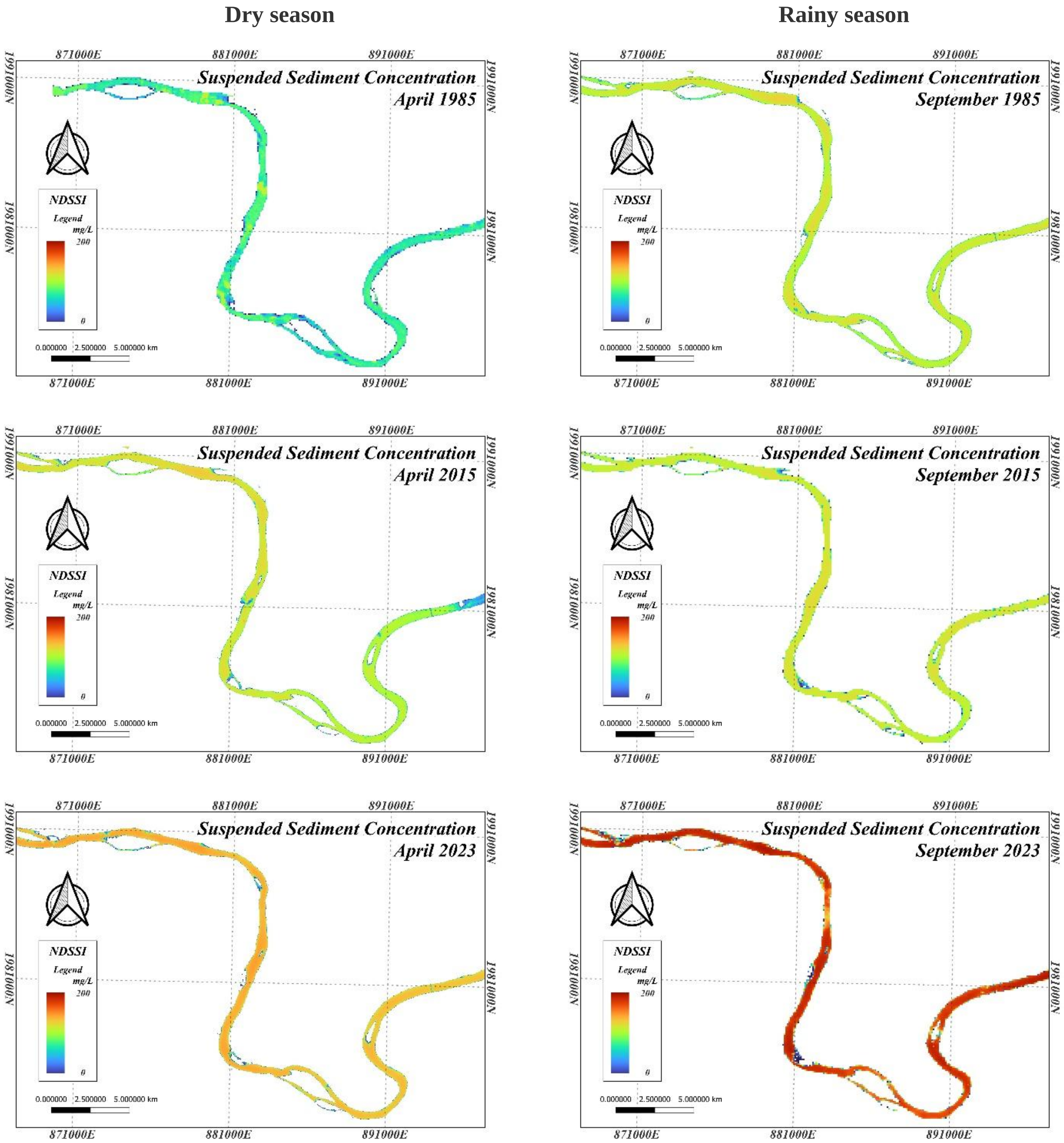

Fig. 5 suspended sediment concentration maps are estimated from Linear regression model.

calibration and refinement are necessary to improve their accuracy and applicability in such dynamic environments. By integrating these insights, environmental monitoring initiatives can adopt tailored approaches to sediment management. The application of reliable indices like NDSSI, combined with supplementary methods to address the limitations of NSMI and NDTI, provides a balanced strategy for informed decision-making in riverine systems.

Future research should address SSC monitoring challenges by focusing on advanced modeling techniques like machine learning and non-linear models, such as neural networks and random forests, to improve predictive accuracy [8], [17], [18], [24]. Integrating multispectral and hyperspectral data from platforms like Sentinel-2 can enhance SSC detection with finer spatial and spectral resolution [10], [12], [14], [19]. Composite models combining NDSSI, NSMI, and NDTI could leverage their strengths while addressing individual limitations [15], [20], [21]. Real-time systems integrating remote sensing and in-situ data could improve temporal coverage and responsiveness to rapid changes [15], [16], [17], [26]. Long-term sediment analysis under climate variability would help adapt monitoring frameworks to shifting precipitation and hydrology, supporting sustainability amid climate change [4], [14], [18], [29].

6. Conclusion

This study evaluated the effectiveness of three remote sensing indices Normalized Difference Suspended Sediment Index (NDSSI), Normalized Suspended Material Index (NSMI), and Normalized Difference Turbidity Index (NDTI) in estimating Suspended Sediment Concentration (SSC) in the Mekong River. The findings revealed that NDSSI was the most reliable index, exhibiting superior R^2 and RMSE values and demonstrating a strong correlation with in situ measurements. These results affirm NDSSI's robustness in capturing sediment concentration variations, making it a valuable tool for monitoring sediment dynamics in large and turbid river systems like the Mekong River.

In contrast, NSMI and NDTI showed lower performance, with moderate to weak correlations to observed SSC values. While NSMI performed better in low-turbidity environments in previous studies, it was less effective under the Mekong River's high sediment concentrations. Similarly, NDTI, designed for turbidity analysis, exhibited limited applicability in the dynamic and sediment-rich conditions of the Mekong River.

The study highlights the unique hydrological and geographic characteristics of the Mekong River, which influence the performance of these indices. While NDSSI is highly recommended for similar environments, further research is needed to refine NSMI and NDTI. Future work could involve optimizing their algorithms, incorporating additional spectral bands, or applying advanced data processing techniques to enhance their accuracy and applicability.

These findings provide valuable insights for sustainable sediment management and environmental monitoring, emphasizing the importance of selecting appropriate remote sensing indices based on the specific characteristics of the study area.

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