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Assessment of Total Suspended Solids (TSS) Pattern in Langkawi using Geospatial Approach

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Abstract: This research explores the application of remote sensing and Geographic Information Systems (GIS) in evaluating TSS patterns in Langkawi, Malaysia, a region known for its ecological significance and tourism appeal. Langkawi's diverse aquatic ecosystems, including rivers, lakes, and coastal waters, face increasing anthropogenic pressures due to rapid urbanization and tourism development. The objectives of this study are to identify the amount of TSS concentration in Langkawi Island and to compare the TSS pattern in different areas in Langkawi Island using Sentinel-2 imagery and in situ data measurement. The integration of field-based water quality measurements complements the remote sensing data, enhancing the accuracy and reliability of the assessment. Findings of the results highlighted TSS patterns in Kilim is higher compared to Pulau Tuba, reflecting distinct environmental dynamics and anthropogenic influences. Highest TSS value in Pulau Tuba is 37.85 mg/L, recorded in February 2023, while the lowest is 9.92 mg/L in October 2022, both at Station 4. The highest TSS value in Kilim is 53.17 mg/L, recorded in October 2022 at Station 2, while the lowest is 6.60 mg/L also in October 2022, at Station 5. The accuracy assessment using Normalized Mean Absolute Error (NMAE) formula shows that all stations are within the tolerance which are below 30%. The NMAE results indicated a high level of agreement between in-situ measurements and satellite-derived data, highlighting the effectiveness of Sentinel-2 in monitoring water quality dynamics over time. The objectives achieved successfully with the final output of TSS pattern maps are produced for both periods (October 2022 and February 2023) in both locations (Pulau Tuba and Kilim). The outcomes hold significant implications for policy development, conservation efforts, and the preservation of Langkawi's unique and fragile aquatic ecosystems in the face of increasing environmental pressures.

Keywords: Water quality, Total Suspended Solids (TSS), Geospatial, Remote Sensing, Geographic Information System (GIS), Langkawi, Malaysia.

1. Introduction

Langkawi, situated in Malaysia's northwest, encompasses a diverse ecosystem of coastal areas, mangroves, and marine environments, vital for the region's biodiversity and economy. Rapid urbanization and tourism activities in Langkawi have raised concerns about the degradation of water quality in its surrounding areas (UNESCO, 2019). Kilim Langkawi and Pulau Tuba Langkawi, two crucial regions within the Langkawi archipelago, have experienced amplified anthropogenic pressures, impacting the fragile balance of their aquatic ecosystems (Hussin et al., 2018). Traditional monitoring approaches are often limited in their spatial coverage and temporal frequency, making it difficult to capture the complex and dynamic patterns of water quality variations in this rapidly changing landscape (Aris et al., 2013). Consequently, there is a pressing need for innovative and integrated approaches to assess and monitor water quality patterns across Langkawi's various aquatic ecosystems.

Numerous studies worldwide have demonstrated the efficacy of geospatial techniques in assessing water quality. Remote sensing, GIS, and spatial analysis have become invaluable tools for monitoring and managing water resources (Rahman et al., 2020). These technologies offer the advantage of providing extensive spatial coverage and temporal data, enabling the evaluation of water quality patterns across large geographic areas (Jensen, 2005).

The application of geospatial approaches to water quality assessment aligns with global initiatives emphasizing the integration of technology and environmental monitoring. The importance of sustainable water management is emphasized

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by the Sustainable Development Goals (SDGs) established by the United Nations (UN, 2015). By employing geospatial tools, this research aims to contribute to the fulfilment of SDG 6, focusing on clean water and sanitation, within the context of Langkawi's environmental conservation efforts.

Specifically focusing on Kilim and Pulau Tuba Langkawi, this study aims to analyze the Total Suspended Solids (TSS) pattern in both areas using Sentinel-2 imagery of 2022 and 2023. The objectives of this study are to identify the amount of Total Suspended Solids (TSS) in Kilim and Pulau Tuba, to compare the Total Suspended Solids (TSS) pattern by using Sentinel-2 imagery and in-situ data in Langkawi and to analyse Total Suspended Solids (TSS) pattern maps of Kilim and Pulau Tuba, Langkawi.

1.1 Study Area

The research was carried out at the Langkawi Island of Kedah state, which is situated on the West Coast of Peninsular Malaysia and looks out over the Malacca Strait. Specifically, the study area encompasses the captivating regions of Kilim and Pulau Tuba Langkawi, situated within the geographical coordinates of Langkawi Island. Kilim Langkawi, located approximately between latitudes 6.4083° N and 99.8308° E, and Pulau Tuba Langkawi, positioned around latitudes 6.3545° N and 99.8000° E, represent ecologically diverse and vital areas within the Langkawi archipelago. The focus area is approximately 8 km from Kilim Geoforest Park seaside and 6 km from Selat Pulau Tuba. These areas showcase rich biodiversity and are distinguished by their unique aquatic ecosystems. However, they are facing growing anthropogenic pressures, primarily stemming from urbanization and tourism activities. Fig. 1 represents the study area of this research.

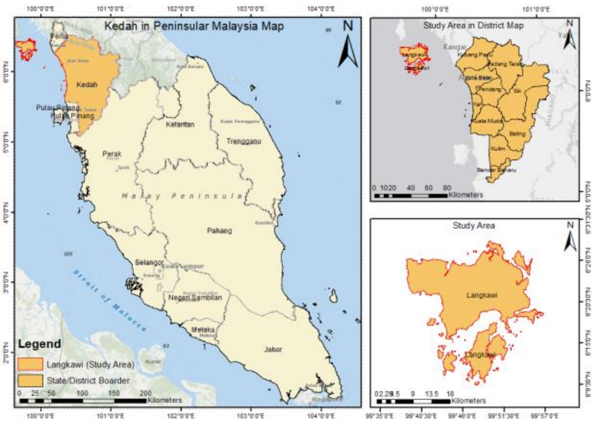

Fig. 1 - Study area map at Langkawi, Malaysia

2. Materials - Data Acquisition

In this study, a combination of satellite imagery and in-situ measurement data was utilized to comprehensively assess Total Suspended Solids (TSS) patterns in the study area encompassing Kilim and Pulau Tuba. Satellite images from the Sentinel-2a mission, accessed through the open-source satellite image website, Copernicus platform (https://dataspace.copernicus.eu/), were employed. These images, captured at a spatial resolution of 10 meters, were obtained for three distinct periods: October 2022 and February 2023. The use of Sentinel-2a imagery provided detailed and consistent spatial coverage of the study area across multiple time points, allowing for the examination of temporal variations in water quality parameters.

Supplementing the satellite data, secondary in-situ measurement datasets were incorporated, covering the same study area and time frames of October 2022 and February 2023. These in-situ measurements, collected on the ground, provided complementary information to validate and enhance the analysis derived from satellite imagery. By combining data from both remote sensing and in-situ measurements, a comprehensive approach was employed to comprehend and assess the dynamics of water quality in Kilim and Pulau Tuba across various seasons and temporal intervals. Table 1 and Table 2 show the secondary in-situ data used for this research.

Table 1 - In-situ measured data at Pulau Tuba

Date	Oct-22		Feb-23	
Stations	TSS (mg/L)	Avg TSS (mg/L)	TSS (mg/L)	Avg TSS (mg/L)
Station 1	11.00	11.44	10.87	11.80
	11.67		11.53	
	11.67		13.00	
Station 2	11.08	10.64	27.67	31.82
	10.75		33.40	
	10.08		34.40	
Station 3	14.67	13.36	31.33	29.52
	13.00		26.22	
	12.42		31.00	
Station 4	9.92	9.92	39.33	37.85
	9.83		33.78	
	10.00		40.44	
Station 5	7.50	11.47	27.22	29.30
	8.75		31.67	
	18.17		29.00	

Table 2 - In-situ measured data at Kilim

Date	Oct-22		Feb-23	
Stations	TSS (mg/L)	Avg TSS (mg/L)	TSS (mg/L)	Avg TSS (mg/L)
Station 1	45.83	46.83	17.78	19.52
	45.17		20.78	
	49.50		20.00	
Station 2	52.67	53.17	22.56	20.67
	52.50		20.00	
	54.33		19.44	
Station 3	18.27	21.49	18.78	14.41
	20.60		15.00	
	25.60		9.44	

Station 4	5.33	7.04	7.27	7.78
	7.00		9.80	
	8.80		6.27	
Station 5	2.80	6.60	9.87	9.56
	7.20		10.00	
	9.80		8.80	

TSS concentration values were measured at each station, with results expressed in mg/L (milligrams per liter). To ensure accuracy, measurements were taken three times at each station, and the average value was calculated.

3. Methodology - Data Processing

This phase involved processing the acquired data to derive meaningful insights into TSS patterns in Langkawi. The process included pre-processing steps, algorithm application, and accuracy assessment. Pre-processing steps encompassed image classification using supervised classification techniques, calculation of band ratios or indices (MNDWI formula), atmospheric correction to eliminate interference, and radiometric enhancement for improved image quality.

Band ratios or indices, such as the Modified Normalized Difference Water Index (MNDWI), were calculated. MNDWI specifically highlights water features by leveraging the spectral differences between green and infrared bands. This index is effective in discriminating against water bodies from other land cover types.

$$MNDWI = \left(\frac{Green - SWIR}{Green + SWIR}\right) \quad (1)$$

Formula number (1) shows the MNDWI specifically used for band ratios calculations.

Where,
Green – Reflectance in Green band (Band 3 for Sentinel-2)
SWIR – Reflectance in Shortwave Infrared band (Band 11 for Sentinel-2)

The study employed an algorithm within the Erdas software modeler, utilizing the formula Y = mx + c, where TSS was calculated using the formula number (2). This algorithm translated satellite data into TSS concentrations, forming a crucial part of the analytical process.

$$TSS = 3.39 \left(\frac{Blue}{Green}\right) - 2.6 \quad (2)$$

Where,
Blue – Reflectance in Blue band (Band 2 for Sentinel-2)
Green – Reflectance in Green band (Band 3 for Sentinel-2)

As per Kowe et al. (2023), an empirical model suitable for Sentinel-2 satellite images was developed to estimate spatial variations in water quality indicators. This model was derived from remote sensing data and in-situ measurements of Total Suspended Solids (TSS), utilizing the water samples collected.

To evaluate the accuracy of the developed algorithms, the Normalized Mean Absolute Error (NMAE) formula was utilized.

$$NMAE\ (\%) = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{x_{esti,i} - x_{meas,i}}{x_{meas}}\right| \times 100 \quad (3)$$

Where,
X*esti* – value of estimated parameter using algorithm
X*meas* – value of measured parameter
N – number of samples

These variables are used in calculations for metrics such as NMAE to gauge the accuracy of the TSS estimation algorithms. The minimum requirement of NMAE value to extract the water quality parameters from remote sensing data is below 30% (Jaelani et al., 2015).

To visualize the spatial variation in TSS, ArcMap software was utilized to create detailed concentration maps. These maps were generated using the Inverse Distance Weighting (IDW) interpolation method, a powerful geostatistical tool that estimates values for unknown points by considering the weighted average of the known data points nearby. IDW is particularly suitable for water quality analysis because it assumes that points closer in proximity are more alike than those farther apart, which aligns well with how pollutants like TSS typically disperse in water bodies. Panhalakr and Jarag (2016) declared that the IDW is even superior and precise as compared to kriging. This method allows for a nuanced representation of TSS concentrations across the study areas, capturing the fine spatial variations that are crucial for understanding the patterns and trends in water quality. Also, a study by Gong et al. (2014) showed that IDW method was more accurate than the kriging approach in predicting some pollutant levels in water.

The overall flow chart of the research methodology can be seen in Fig. 2.

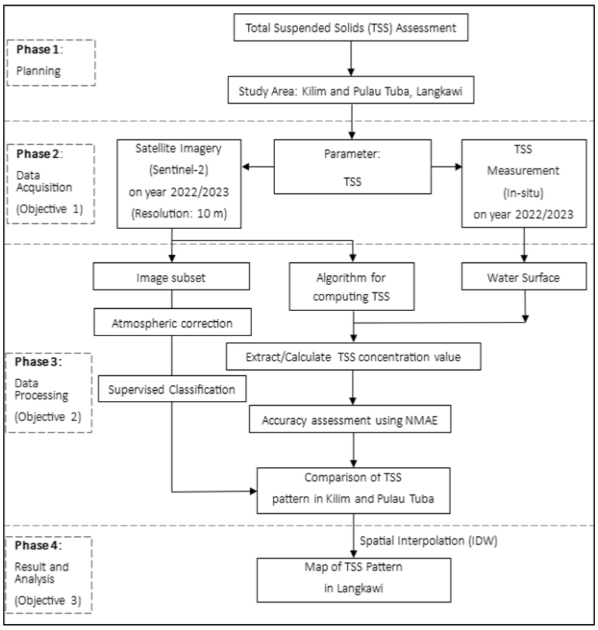

Fig. 2 - Methodology flow chart

4. Result and Discussion

4.1 In-situ observations for Total Suspended Solids (TSS) concentration

In October 2022 and February 2023, in-situ measurements for Total Suspended Solids (TSS) were conducted at two locations: Pulau Tuba and Kilim. Each location had five sampling stations established for data collection. At each station, TSS concentration data were collected, with the aim of understanding the variability of TSS levels in the study area.

Pulau Tuba as a focal point for the study, covering approximately 6 km along Selat Pulau Tuba. Five sampling stations were designated across the area, with coordinates and the results of TSS concentration values provided in Table 1. Data collection occurred on October 24, 2022, and February 21, 2023, between 3 pm to 5 pm, with a five-month gap between collections. This interval was deemed suitable to capture seasonal variations in TSS levels. The choice of time (3 pm to 5 pm) aimed to minimize the effects of diurnal fluctuations.

Table 1 shows the in-situ data measured at Pulau Tuba. Station 1 recorded TSS concentrations of 11.44 mg/L in October 2022 and 11.80 mg/L in February 2023. Station 2 exhibited TSS levels of 10.64 mg/L in October 2022, which notably increased to 31.82 mg/L in February 2023. Similarly, at station 3, TSS concentrations rose from 13.36 mg/L in October 2022 to 29.52 mg/L in February 2023. Notably, there were significant differences observed between TSS concentrations in October 2022 and February 2023. For instance, Station 4 experienced a significant rise in TSS levels, with concentrations climbing from 9.92 mg/L in October 2022 to 37.85 mg/L in February 2023. This notable difference could be attributed to various factors such as seasonal changes, increased anthropogenic activities, or variations in weather patterns. Lastly, station 5 observed TSS concentrations of 11.47 mg/L in October 2022 and 29.30 mg/L in February 2023.

Overall, the higher TSS concentrations recorded in February 2023 compared to October 2022 at Pulau Tuba suggest a potential seasonal trend or environmental changes influencing water quality in the study area. Fig. 3 shows the summary of in-situ data for TSS value at Pulau Tuba in a bar graph form to illustrate the comparison in both periods.

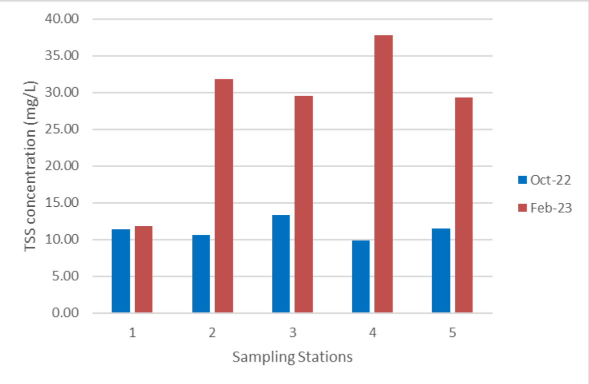

Fig. 3 - Bar graph of temporal TSS concentration value at Pulau Tuba, Langkawi for in-situ measurement

Five sampling stations were strategically positioned in Kilim Langkawi, with coordinates meticulously recorded for precise location tracking. Data collection took place on October 25, 2022, and February 19, 2023, between 3 pm to 5 pm, ensuring consistency and minimizing environmental variations during sampling. This time interval was deemed suitable for data collection due to stable lighting conditions and minimal interference from human activities, facilitating accurate and reliable measurements.

As shown in Table 2, Station 1 recorded TSS concentrations of 46.83 mg/L in October 2022, which notably decreased to 19.52 mg/L in February 2023. Similarly, station 2 exhibited TSS levels of 53.17 mg/L in October 2022, which decreased to 20.67 mg/L in February 2023. Station 3 showed a decrease from 21.49 mg/L in October 2022 to 14.41 mg/L in February 2023. Conversely, station 4 displayed minimal variation, with TSS concentrations of 7.04 mg/L in October 2022 and 7.78 mg/L in February 2023. This consistency suggests stable environmental conditions or consistent pollutant sources at this location. Station 5 observed TSS concentrations of 6.60 mg/L in October 2022 and 9.56 mg/L in February 2023.

Overall, these fluctuations in TSS concentrations across the Kilim study area emphasize the dynamic nature of water quality parameters in this region. Fig. 4 shows the summary of in-situ data for TSS value at Kilim in a bar graph form to illustrate the comparison in both periods.

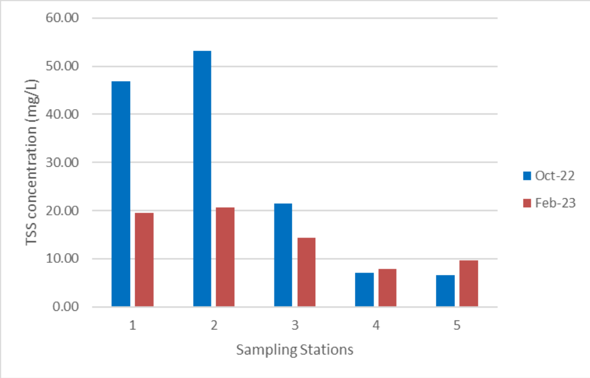

Fig. 4 - Bar graph of temporal TSS concentration value at Kilim, Langkawi for in-situ measurement

4.2 Sentinel-2 image processing for Total Suspended Solids (TSS) assessment

Table 3 shows the results of extracted TSS concentration values from satellite images for each station on both dates at Pulau Tuba.

Table 3 - TSS concentration values extracted at Pulau Tuba, Langkawi

Date	Oct-22	Feb-23
Stations	TSS (mg/L)	TSS (mg/L)
Station 1	10.73	12.20
Station 2	10.24	31.43
Station 3	14.07	29.72
Station 4	9.55	37.48
Station 5	11.32	29.61

Station 1 exhibited 10.73 mg/l (Oct 22) and 12.20 mg/l (Feb 23), while station 2 showed 10.24 mg/l (Oct 22) and notably increased to 31.43 mg/l (Feb 23). Station 3 had 14.07 mg/l (Oct 22) and 29.72 mg/l (Feb 23), whereas station 4 displayed 9.55 mg/l (Oct 22) and remarkably rose to 37.48 mg/l (Feb 23). The TSS values at station 5 were 11.32 mg/l (Oct 22) and 29.61 mg/l (Feb 23). The observed increasing pattern from October 2022 to February 2023 across all stations underscores significant fluctuations in TSS levels.

In Kilim, TSS concentration values in mg/L for all sampling stations were extracted, with results displayed in Table 4.

Table 4 - TSS concentration values extracted at Kilim, Langkawi

Date	Oct-22	Feb-23
Stations	**TSS (mg/L)**	**TSS (mg/L)**
Station 1	47.11	19.33
Station 2	52.87	21.03
Station 3	21.85	14.21
Station 4	8.14	8.32
Station 5	7.23	9.17

As a result, as shown in Table 4, Station 1 registered 47.11 mg/l (Oct 22) and notably decreased to 19.33 mg/l (Feb 23), while station 2 exhibited 52.87 mg/l (Oct 22) and decreased to 21.03 mg/l (Feb 23). Station 3 recorded 21.85 mg/l (Oct 22) and 14.21 mg/l (Feb 23), and station 4 displayed consistent values of 8.14 mg/l (Oct 22) and 8.32 mg/l (Feb 23). Station 5 had 7.23 mg/l (Oct 22) and 9.17 mg/l (Feb 23). The observed decreasing trend from October 2022 to February 2023 across all stations suggests potential changes in sediment dynamics or water flow patterns in the Kilim area, warranting further investigation.

4.3 Accuracy assessment using Normalized Mean Absolute Error (NMAE)

The accuracy assessment for Pulau Tuba and Kilim involved comparing the NMAE percentages for TSS concentrations for October 2022 and February 2023. Table 5 represents the results of NMAE in percentage value for both dates at Pulau Tuba, while Table 6 represents the NMAE results at Kilim.

Table 5 - Results for percentage of NMAE at Pulau Tuba, Langkawi

Stn	N	Oct-22		NMAE (%)	Feb-23		NMAE (%)
		***X**esti*	***X**meas*		***X**esti*	***X**meas*	
1	3	10.73	11.44	-2.07	12.20	11.80	1.13
2	3	10.24	10.64	-1.25	31.43	31.82	-0.41
3	3	14.07	13.36	1.77	29.27	29.52	-0.28
4	3	9.55	9.92	-1.24	37.48	37.85	-0.33
5	3	11.32	11.47	-0.44	29.61	29.30	0.35

The results, presented in percentage form, showed that for October 2022, the highest NMAE percentage was 2.07% at Station 1, while the lowest was 0.44% at Station 5. For February 2023, the highest NMAE percentage remained at Station 1 with 1.13%, and the lowest was 0.28% at Station 3. The consistently higher NMAE percentages at Station 1 for both dates could be due to greater variability in TSS concentrations or specific local environmental factors affecting this station. Importantly, all **NMAE percentages for each station were below 30%**, indicating that the TSS data derived from satellite imagery are **acceptably accurate** when compared to in-situ measurements. Overall, the NMAE assessment confirms the reliability of the satellite-derived TSS values for this study area.

Table 6 - Results for percentage of NMAE at Kilim, Langkawi

Stn	N	Oct-22		NMAE (%)	Feb-23		NMAE (%)
		***X**esti*	***X**meas*		***X**esti*	***X**meas*	
1	3	47.11	46.83	0.20	19.33	19.52	-0.32
2	3	52.87	53.17	-0.19	21.03	20.67	0.58
3	3	21.85	21.49	0.56	14.21	14.41	-0.46
4	3	8.14	7.04	5.21	8.32	7.78	2.31
5	3	7.23	6.60	3.18	9.17	9.56	-1.36

For October 2022, the highest NMAE percentage was 5.21% at Station 4, while the lowest was 0.19% at Station 2. In February 2023, the highest NMAE percentage remained at Station 4 with 2.31%, and the lowest was 0.32% at Station 1. The consistently higher NMAE percentages at Station 4 for both dates may be due to more significant environmental fluctuations or localized factors affecting TSS concentrations at this station. Despite these variations, all **NMAE percentages for each station were below 30%**, indicating that the satellite-derived TSS data are **acceptably accurate** compared to in-situ measurements. In summary, the NMAE assessment confirms the reliability of the satellite-derived TSS values for the Kilim Langkawi study area.

4.4 Maps of Total Suspended Solids (TSS) pattern in Pulau Tuba and Kilim

In this results section, the focus is on the spatial distribution maps of Total Suspended Solids (TSS) concentration across Pulau Tuba and Kilim in Langkawi, assessed during two different periods: October 2022 and February 2023. To visualize the spatial variation in TSS, ArcMap software is utilized to create detailed concentration maps.

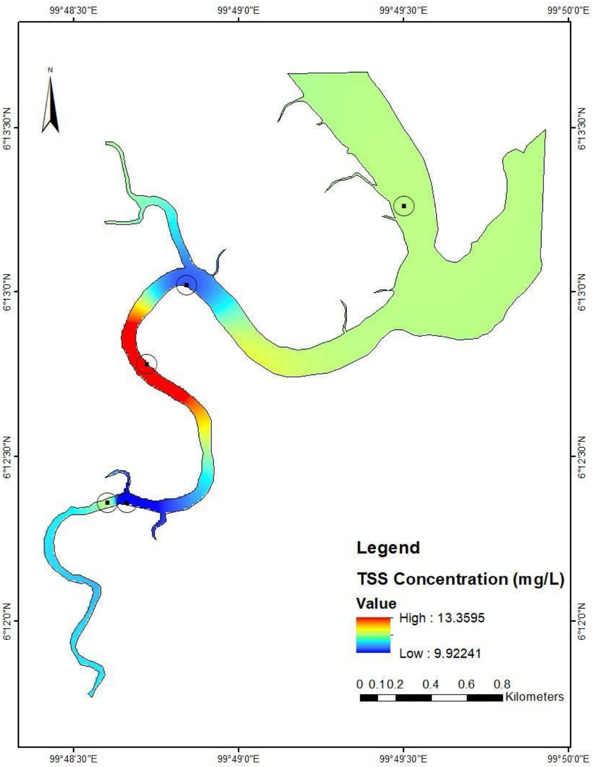

Fig. 5 - TSS Concentration Pattern Map at Pulau Tuba Langkawi on October 2022 by using in-situ data

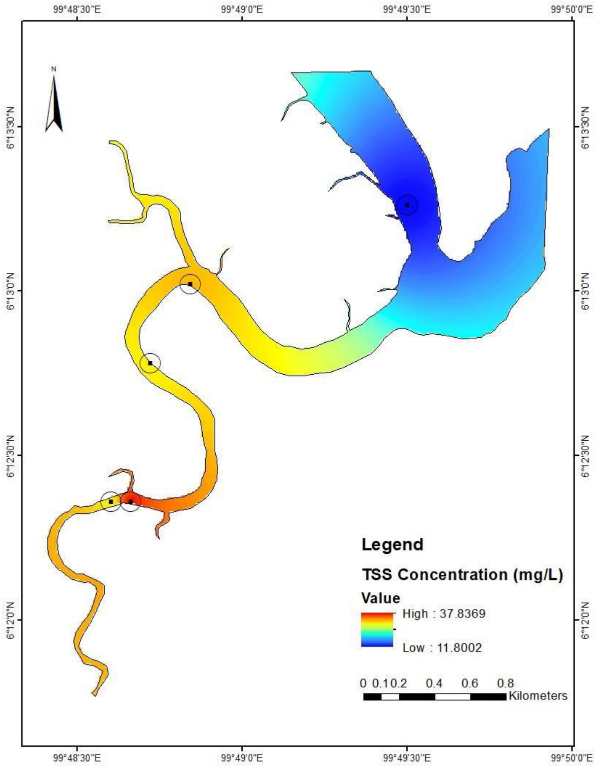

Fig. 7 - TSS Concentration Pattern Map at Pulau Tuba Langkawi on February 2023 by using in-situ data

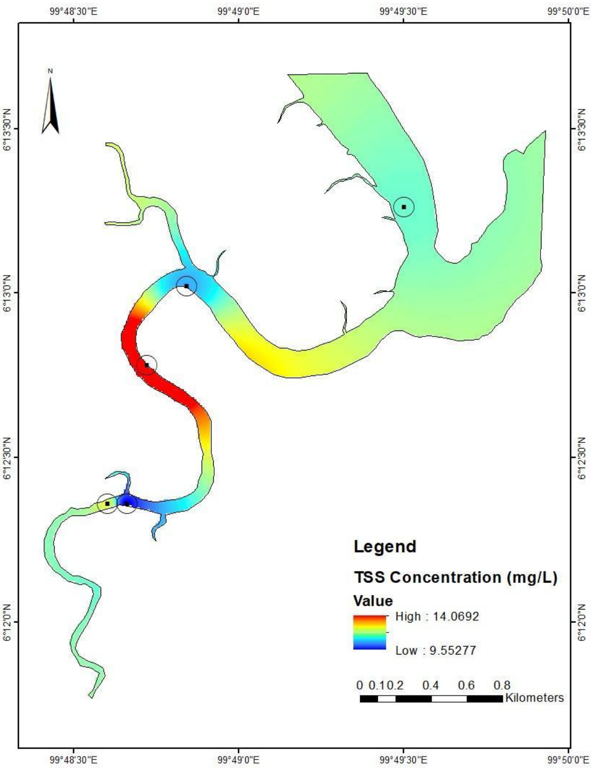

Fig. 6 - TSS Concentration Pattern Map at Pulau Tuba Langkawi on October 2022 by using Sentinel 2 data

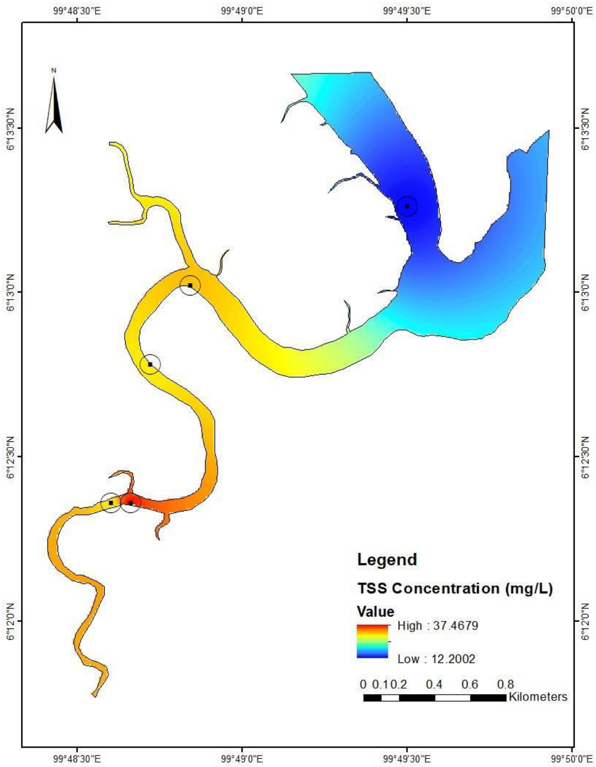

Fig. 8 - TSS Concentration Pattern Map at Pulau Tuba Langkawi on February 2023 by using Sentinel 2 data

The spatial distribution and comparison of TSS concentration patterns at Pulau Tuba Langkawi were examined using both in-situ measurements and Sentinel-2 satellite data. Fig. 5 presents the TSS Concentration Pattern Map for October 2022 based on in-situ data, highlighting localized measurements taken directly from the water. This map provides detailed insights into specific areas with varying TSS levels, reflecting the actual conditions observed on-site during the sampling period.

In contrast, Fig. 6 depicts the TSS Concentration Pattern Map for the same period, October 2022, derived from Sentinel-2 satellite imagery. The satellite data offers a broader and more continuous spatial coverage compared to the discrete in-situ sampling points. While the overall patterns in both maps are consistent, with higher TSS concentrations observed near certain coastal areas, the Sentinel-2 data captures a more expansive view, potentially identifying variations missed by the limited in-situ measurements. This comparison highlights the advantage of remote sensing in providing comprehensive spatial assessments of water quality over large areas.

For February 2023, Fig. 7 shows the TSS Concentration Pattern Map generated from in-situ data, capturing the TSS distribution at specific locations across Pulau Tuba. This map again underscores the precision and accuracy of direct field measurements.

However, when compared with Fig. 8, which displays the TSS Concentration Pattern Map for the same month derived from Sentinel-2 data, there are observable differences in the spatial extent and detail of TSS distribution. The TSS pattern at Station 1 shows the low TSS values, near the estuary opening and surrounded by mangroves. Mangrove forests in estuaries play an important role in protecting the shoreline and river from erosion, thus reducing any sediment from entering the waters (Le Nguyen & Luong, 2019). The Sentinel-2 map indicates a more widespread and higher concentration of TSS across the study area, consistent with the increasing trend noted in in-situ data but providing a more extensive spatial context.

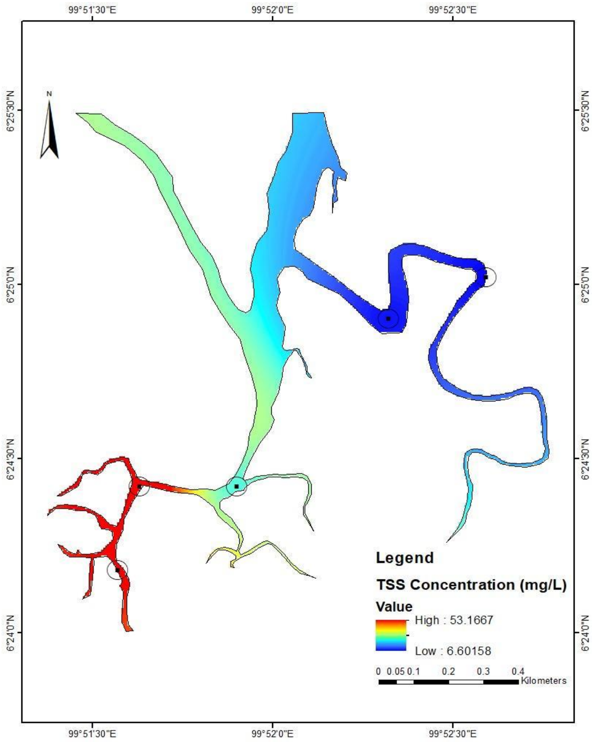

Fig. 9 - TSS Concentration Pattern Map at Kilim Langkawi on October 2022 by using in-situ data

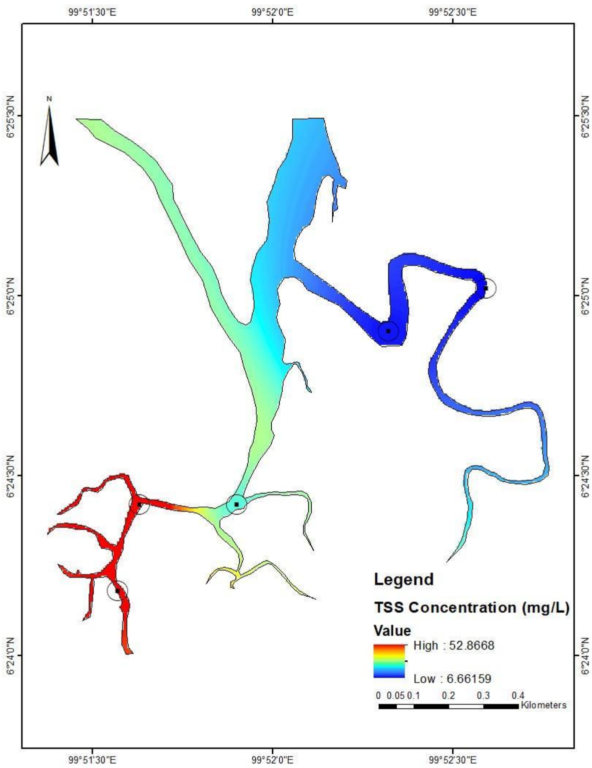

Fig. 10 - TSS Concentration Pattern Map at Kilim Langkawi on October 2022 by using Sentinel 2 data

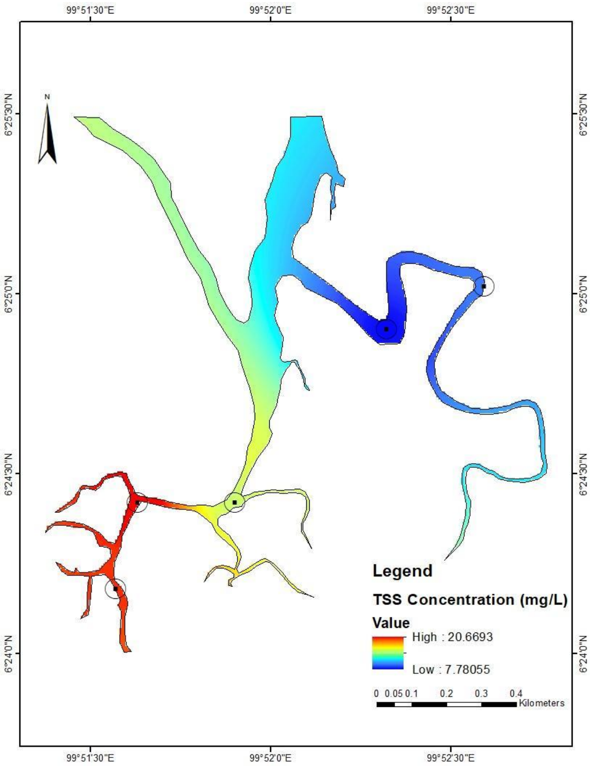

Fig. 11 - TSS Concentration Pattern Map at Kilim Langkawi on February 2023 by using in-situ data

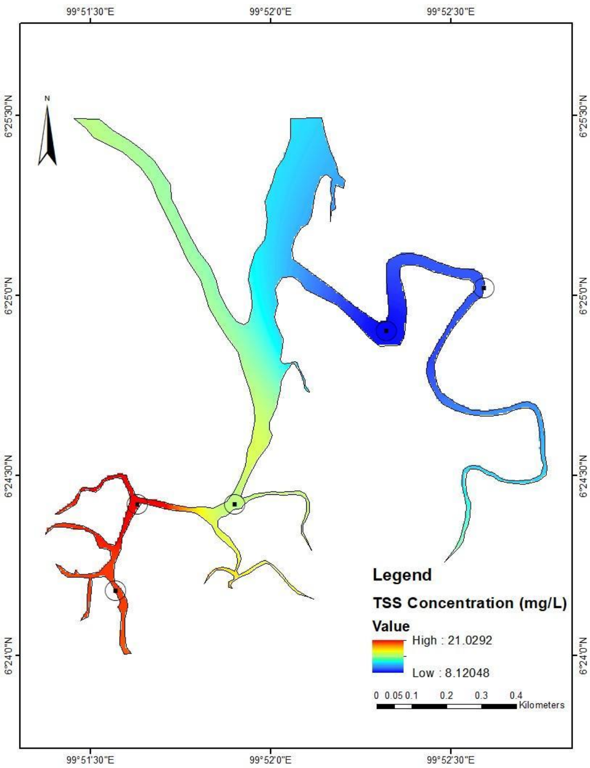

Fig. 12 - TSS Concentration Pattern Map at Kilim Langkawi on February 2023 by using Sentinel 2 data

The TSS concentration patterns at Kilim Langkawi for October 2022 and February 2023 were analysed using both in-situ measurements and Sentinel-2 satellite data. Fig. 9 presents the TSS Concentration Pattern Map for October 2022 based on in-situ data. This map reflects precise TSS measurements at specific sampling stations within the Kilim area, providing detailed insights into the spatial distribution of TSS at those exact points. The results show localized variations in TSS concentrations, which are critical for understanding water quality at a micro-scale.

In contrast, Fig. 10 illustrates the TSS Concentration Pattern Map for the same period, October 2022, derived from Sentinel-2 satellite data. This map highlights the capability of Sentinel-2 to offer a more extensive and continuous spatial representation of TSS concentrations across the entire Kilim area. The broader coverage of the satellite data captures a more comprehensive view of TSS distribution, including areas between the in-situ sampling points, which might show additional variations in TSS levels. The significant decreasing trend of TSS concentration values from October 2022 to February 2023 at Kilim, may be due to the rainfall rate at Langkawi. The monsoon season in Langkawi falls between September and October, receiving the highest rainfall in the whole year (Jabatan Meteorologi Malaysia). Heavy rainfall can lead to soil erosion, carried into rivers, increasing TSS (Hashim et al., 2023)

For February 2023, Fig. 11 shows the TSS Concentration Pattern Map based on in-situ data, providing a snapshot of TSS levels at specific stations in Kilim. This map reveals the precise TSS conditions observed during the February sampling. When compared with Fig. 12, which displays the TSS Concentration Pattern Map for the same period derived from Sentinel-2 data. There are anthropogenic activities observed near Station 1 and 2, such as tourist spots. The effects of land use are essentially the effects of human activities (human activities that take place on land area) on water quality (Chen et al., 2021).

5. Conclusion

In summary, this study presented a comprehensive analysis of Total Suspended Solids (TSS) concentration patterns in Langkawi, specifically focusing on Pulau Tuba and Kilim, using both in-situ measurements and Sentinel-2 satellite imagery. The in-situ data collection took place in October 2022 and February 2023, covering five sampling stations at each location. Highest TSS value in Pulau Tuba is 37.85 mg/L, recorded in February 2023, while the lowest is 9.92 mg/L in October 2022, both at Station 4. Highest TSS value in Kilim is 53.17 mg/L, recorded in October 2022 at Station 2, while the lowest is 6.60 mg/L also in October 2022, at Station 5. Findings of the results highlighted TSS patterns in Kilim are higher compared to Pulau Tuba, reflecting distinct environmental dynamics and anthropogenic influences. This seasonal increase in TSS was attributed to factors such as changes in weather patterns, tidal movements, and anthropogenic activities. The use of Sentinel-2 imagery facilitated the creation of detailed TSS concentration maps through spatial distribution tools in ArcMap, utilizing the IDW interpolation method. This method proved suitable for water quality analysis due to its ability to create smooth, continuous surfaces that represent the spatial variability of TSS concentrations effectively.

The accuracy assessment of TSS concentration results using the Normalized Mean Absolute Error (NMAE) indicated a high level of agreement between in-situ measurements and satellite-derived data. For Pulau Tuba, the

NMAE values ranged from 0.44% to 2.07% in October 2022 and 0.28% to 1.13% in February 2023, all well below the 30% threshold, confirming the reliability of the satellite data. Similarly, for Kilim, the NMAE values ranged from 0.19% to 5.21% in October 2022 and 0.32% to 2.31% in February 2023, demonstrating acceptable accuracy. The TSS concentration maps produced from both in-situ and Sentinel-2 data provided a detailed spatial representation of water quality conditions, enabling a clear comparison of temporal and spatial patterns. Overall, the combined use of in-situ measurements and remote sensing data enhanced the understanding of TSS dynamics in Langkawi, supporting better water quality management and decision-making.

In conclusion, this study has successfully achieved all the objectives. This study significantly contributes to the field of environmental science by leveraging advanced geospatial technologies to enhance our understanding of water quality dynamics in Langkawi.

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