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Improving Seasonal Distribution Estimation of Total Suspended Solids in The Madura Strait Waters, Indonesia

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Abstract: High TSS causes siltation around coastal areas in the Madura Strait. TSS impacts water quality and habitat health. It's necessary to know that TSS distribution can vary each season. The algorithm detects TSS distribution by processing Landsat-8 satellite image data. However, existing algorithms are sometimes only suitable for some instances, so the results do not correspond to actual conditions. Therefore, this paper wants to build a better detection model using Laili's algorithm to determine whether satellite image analysis can explain the exact conditions. Laili's algorithm detection was validated and corrected against field data via a correlation test. It's necessary to know the spatial distribution pattern of data attribute values using the Moran Index. The results TSS in the dry season is 5-18 mg/L and covers an area of up to 4 km; in the rainy season, it is 5-22 mg/L and can cover an area of up to 7.8 km. Moran's Index results show that spatial autocorrelation in the distribution pattern results in a cluster pattern. These results show that the detection model is relatively reasonable and can be used as training data to detect the distribution of TSS in the Madura Strait in subsequent years.

Keywords: Madura strait; Moran's index; Total Suspended Solids (TSS); TSS algorithm; TSS distribution

Introduction

The hydrological cycle process brings suspended material from the land into the river (Warrick, 2020). The amounts of solid particles suspended in water but not dissolved are known as total suspended solids (TSS) (Andrio et al., 2024). Ocean currents can distribute material that drifts into rivers and accumulates in estuaries to coastal and broader waters (Retnaningdyah et al., 2019). The movement of currents is dynamic and influenced by the wind in each season, so the distribution of sediments can be different (Cai et al., 2022). A river mouth is the largest source or contributor of suspended particles (Luo et al., 2021). The Madura Strait is a semi-enclosed sea that separates two land masses so that the pattern of water mass movement makes sediments entering the waters only be distributed in the strait. Water conditions in the Madura Strait often change every season, and some locations have a high level of sedimentation, for example, the coast of Probolinggo and Sidoarjo which experience siltation (Kusmanto et al., 2016; Ikhwani et al., 2018).

TSS can also act as a transporter of contaminants, which can cause problems with water quality and habitat (Mamun et al., 2022; Elvitriana et al., 2023). These particles can affect light penetration into water, cause water turbidity, disrupt aquatic life, and impact to coral reef ecosystems (Supardiono et al., 2023; Yao et al., 2022). TSS in the water can cause the degradation of coral reef ecosystems (Putra et al., 2023). This is one of the factors

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that causes a decrease in habitat quality (Kawanishi et al., 2015). Sedimentation attached to coral reefs is challenging to remove, and this will reduce the metabolism and immunity of coral reefs (Rodgers et al., 2021). So, TSS measurements are essential in water quality monitoring because they can provide information on pollution levels, soil erosion rates, and the effects of human activities on aquatic ecosystems (Yustika et al., 2019; Utama et al., 2023). Sediment buildup in coastal areas can change the length of the shoreline. TSS is carried by currents and waves, these particles settle on the seafloor and change the topographical shape of the seafloor (Anthony & Aagaard, 2020). Therefore, knowing the sources and distribution of TSS pollutants will be a priority.

Using electromagnetic from the sun can be used to detect events on Earth (Akbar et al., 2024). TSS in water can be detected with remote sensing by using Landsat-8 satellite images to determine the conditions of the seas (Adjovu et al., 2023; Fitri et al., 2023). Based on this, spatial detection is a powerful method in mapping TSS dynamics over a large area (Yuanita et al., 2011). The ability of electromagnetic waves to detect suspended solids has limitations because they cannot penetrate non-transparent solids; therefore, if there is a high build-up of suspended particles, it is difficult to detect them and estimate their value accurately (Molijn et al., 2019).

The accuracy of the data is relatively low due to the limitations of electromagnetic wave capabilities and the long distance between the sensor and the object being detected; however, it is necessary to perform several correction processes to obtain a good value and be close to the actual situation (Syah, 2010). Spatial detection has several drawbacks that need to be considered. Spatial detection is complex and requires a deep understanding of the analysis process and the resulting interpretation (Wen et al., 2021). Spatial detection relies heavily on accurate and up-to-date data to reduce error and bias in the analysis process (Santoro et al., 2015). The correction starts from the influence of the atmosphere, cloud cover, and ground truth simultaneously as the satellite image capture. Using ground truth can improve the model in determining the actual value by field conditions. Different seasons cause the calculation of TSS detection in each season to be different (Miranda et al., 2021).

Spatial sediment detection research is an effort to map and analyze the distribution of sediment in an area in detail. Based on previous research, detecting TSS distribution from the source, coastal areas, and spreading it to large waters such as straits has never been done. Therefore, data estimation needs to use a detection model at a location adjacent to the location being studied, and periodic model updates are required to provide accurate results (Chen et al., 2020). This research is useful for mitigation, natural resource management, and environmental change monitoring (Chairani et al., 2023). By understanding sediment distribution, we can make better decisions in environmental management and sustainable development. Therefore, this paper aims to examine the seasonal distribution of TSS in more expansive waters, with the Madura Strait, as a case study.

Method

Material

Total Suspended Solid (TSS) is a water quality parameter that will impact the environment if the amount is excessive (Susanto et al., 2023). Based on information on the coastal areas around the Madura Strait waters that have experienced siltation, it is necessary to know how much TSS levels enter the seas and how large the distribution of TSS is in the waters (Figure 1). This research is a baseline study based on information. Research and observation activities and primary and secondary data collection were carried out in August 2022 and February 2023.

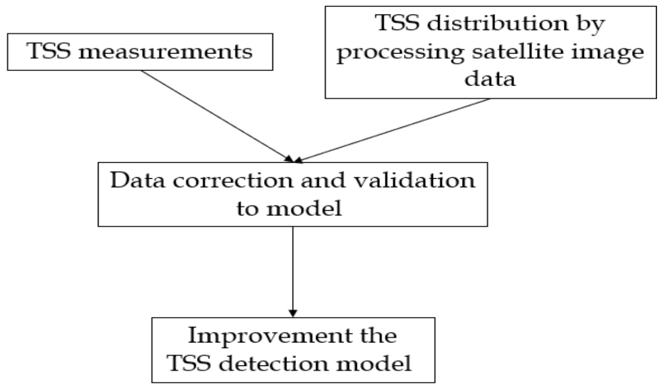

Figure 1. Research flow

The primary source of sediment entering the water comes from the estuary, so locations near the estuary need to be considered to estimate TSS distribution. The location of the sampling station was determined by a purposive sampling method with several criteria, i.e., the river's width, the length of the river flow, and the contributor or source of sediment to the coast and ocean. Field measurements are used for validating TSS detection so that the location of the sampling points covers all sides of the Madura Strait waters from north to south (Figure 2).

The rivers used as research objects were the river of Blega in Sampang District, the Kemuning in Sampang District, the Saroka in Sumenep District, the Jagir in Surabaya City, the Porong in Sidoarjo District, the Kramat in Probolinggo District, and the Sampean in Situbondo District. River water samples were carried out in August 2022 (the peak of the dry season) and February 2023 (the rainy season). The determination of the season refers to precipitation data from the National Aeronautics and Space Administration (NASA) (NASA, 2022, 2023) (Figure 3). Moreover, TSS was measured with laboratory measurements.

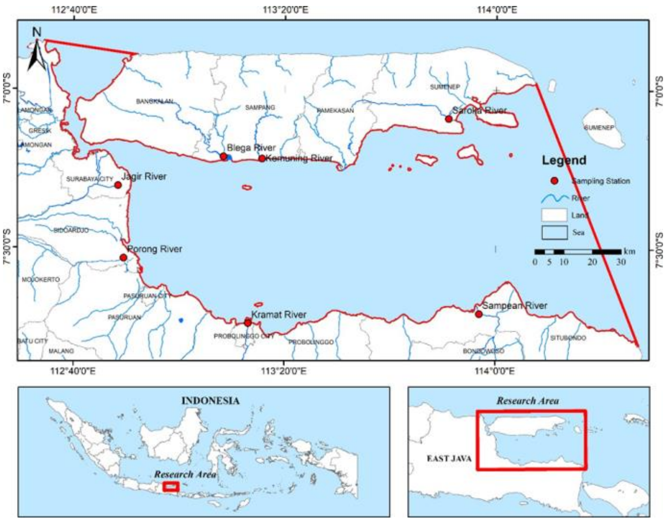

Figure 2. Map of the research study

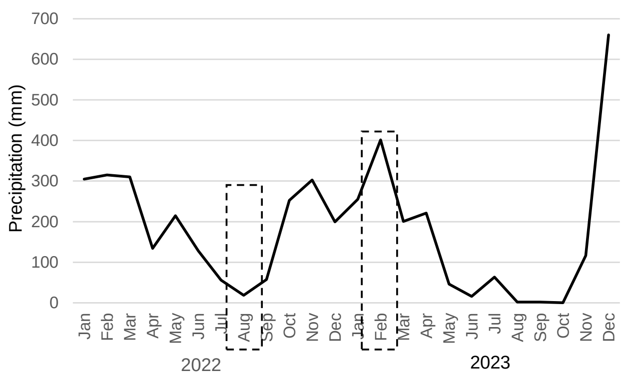

Figure 3. Distribution of annual precipitation in East Java (Source: NASA (2022, 2023))

Total Suspended Solid Measurements

According to the American Public Health Association (APHA) (Rice et al., 2017), the sampling process can use plastic bottles or glass bottles, and storage can be done for up to 7 days in cold conditions ≤ 6°C. All equipment used during sampling and analysis in the laboratory must be rinsed to prevent contamination. The TSS concentration was measured using the gravimetric principle or by weighing with the SNI 06-6989.3-2004 method (Indonesian National Standardization Agency, 2004). The filter paper was calculated by dry weight, and then 100 mL of sample water was filtered. Then, the filter paper was calculated dry weight after the sample filtering process; the calculations used:

$$TSS\left(\frac{mg}{L}\right) = \frac{(A - B) \times 1000}{\text{Sample volume (ml)}} \quad (1)$$

where A is the final weight (filter + residue) in units of (mg), and the B value is the initial weight of the filter in units of (mg).

Analysis Data

TSS Distribution by Processing Satellite Image Data

Landsat-8 satellite imagery was used for TSS distribution analysis. Raw satellite image data was corrected before processing. The correction of satellite image pixel values or digital numbers was carried with radiometric correction to correct inappropriate pixel values caused by several factors (Hidayah & Nuzula, 2019). Radiometric correction is top-of-atmosphere reflectance (TOA), i.e. (Laili et al., 2015):

$$\rho\lambda' = M\rho * Qcal + A\rho \quad (2)$$

where $\rho\lambda'$ is the TOA reflectance. $M\rho$ is the reflectance multiplicative scaling factor for the band taken from the reflectance multiband N in the metadata of the blue and red bands for which TOA values are calculated. $A\rho$ is the reflectance additive scaling factor for the band taken from the reflectance add band N value in the metadata on the blue and red bands for which the TOA value was calculated. Qcal was the band's pixel value or digital number for which the TOA value was to be calculated. Satellite image data that have been atmospherically corrected were subsequently analyzed using the TSS algorithm to map the distribution developed by Laili et al. (2015). This algorithm was used in a similar location, and the algorithm can predict TSS in the seas well (91%) (Novitasari et al., 2020) with the following process:

$$TSS\left(\frac{mg}{L}\right) = 31.42 * \left(\frac{\text{Log(RRS2)}}{\text{Log (RRS4)}}\right) - 12.719 \quad (3)$$

where RRS2 is the corrected reflectance value of the blue band, and RRS4 is the corrected reflectance value of the red band.

Data Correction and Validation to Improve the Detection Model

The results of the TSS analysis were subsequently corrected against field data via a correlation test. The results of satellite image analysis with field measurements were compared to determine how much the results of satellite image analysis can explain the actual conditions. It is necessary to know the spatial distribution pattern of data attribute values using the Moran Index. Suppose the results of a good or positive data distribution pattern are obtained. In that case, the data has the same characteristics and tends to be close to other data so different data distributions can also be interpreted with the same model (Wibowo, 2022). The hypothesis test for Moran's Index is H0 = no spatial autocorrelation and H1 = There is spatial autocorrelation. The results of this test will lead to the creation of a new equation for TSS analysis with better satellite imagery (Budianto & Hariyanto, 2017).

Result and Discussion

Based on satellite imagery data, TSS was detected in the waters of the Madura Strait from the coast to the ocean range of 12-22 mg/L for the dry season and 12-23 mg/L for the rainy season (Figure 4 a1&b1). The results show values that do not differ significantly between seasons and in the middle of the Madura Strait Sea detected relatively high. Nevertheless, the TSS concentration field measurements show that the highest average TSS concentration in the dry season was in the Blega River at 24.6 mg/L, while the lowest was in the Kramat River at 5.3 mg/L (Table 1).

The highest average TSS concentration in the rainy season was in the Saroka River, at 40.6 mg/L, while the lowest was in the Kramat and Sampean Rivers, at 4.3 mg/L. In general, during the rainy season, the intensity of rainfall is more significant, causing the volume of water and river discharge to increase (Melanwati et al., 2023). This condition can increase the concentration of suspended solids per unit liter due to flushing by natural river discharge (Kuznietsov & Biedunkova, 2023). Conversely, the dry season tends to have a suspended solids concentration per unit liter can be lower. However, a high TSS concentration can cause sedimentation (Surapati & Mizwar, 2020).

These results were validated to build a better TSS detection model. The validation test used a correlation calculation that compares the processed image data with ground truth TSS data in the field. This approach was used to determine the extent of the image data's closeness or goodness of fit.

Table 1. Total Suspended Solids (TSS) measurement results (mg/L)

Station location	Dry season			Average TSS (mg/L)	Rainy season			Average TSS (mg/L)
	Point 1 (mg/L)	Point 2 (mg/L)	Point 3 (mg/L)		Point 1 (mg/L)	Point 2 (mg/L)	Point 3 (mg/L)	
Blega River, Sampang District	24	27	23	24.67	21	26	18	21.67
Kemuning River, Sampang District	18	16	14	16	15	18	6	13
Saroka River, Sumenep District	24	18	12	18	39	63	20	40.67
Jagir River, Surabaya City	20	10	16	15.33	8	5	6	6.33
Porong River, Sidoarjo District	10	8	6	8	4	3	8	5
Kramat River, Probolinggo District	5	4	7	5.33	3	4	6	4.33
Sampean River, Situbondo District	6	7	9	7.33	5	4	4	4.33

Note: TSS = The Total Suspended Solid (mg/L)

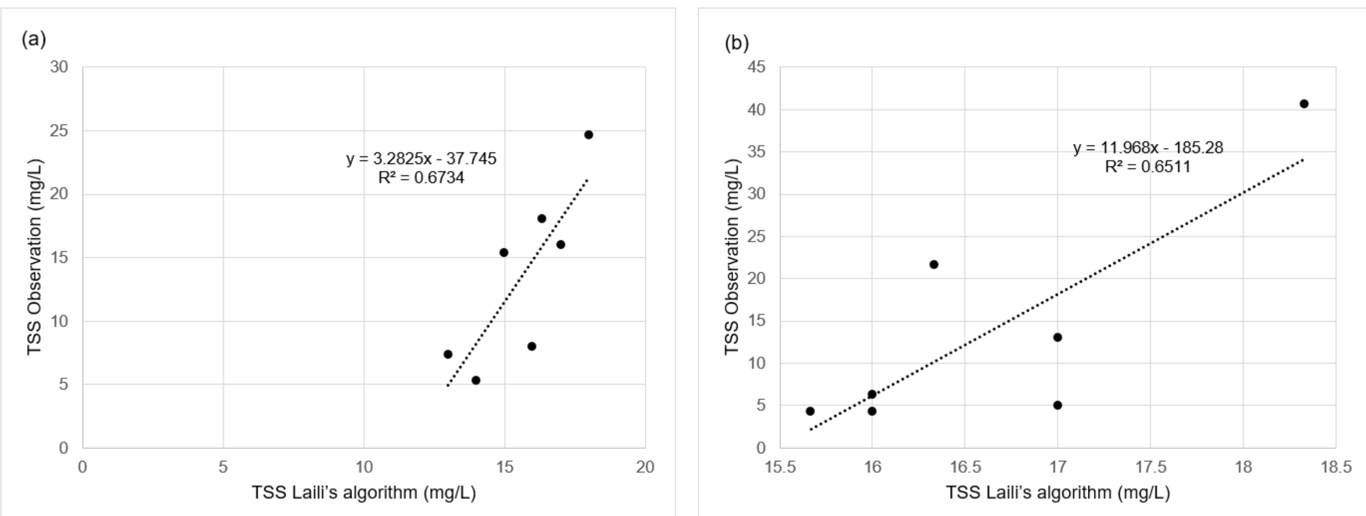

Figure 4. Validation test of the total suspended solid value by algorithm of Laili et al. (2015) with TSS field data. a. in the dry season, b. in the rainy season

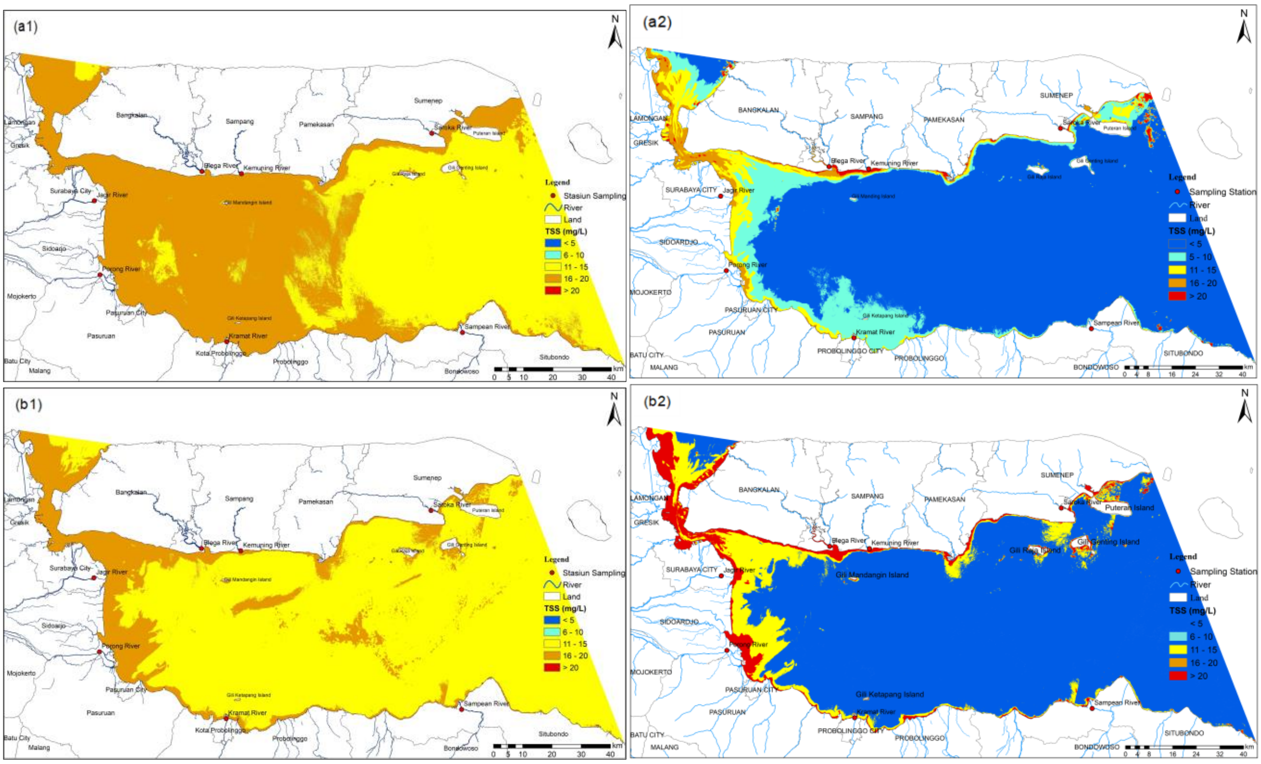

Figure 5. Distribution of total suspended solids in the Madura Strait waters. Note: (1) using the algorithm of Laili et al. (2015) (left) and (2) using the new algorithm model (right); and (a) in the dry season (top) and (b) in the rainy season (bottom)

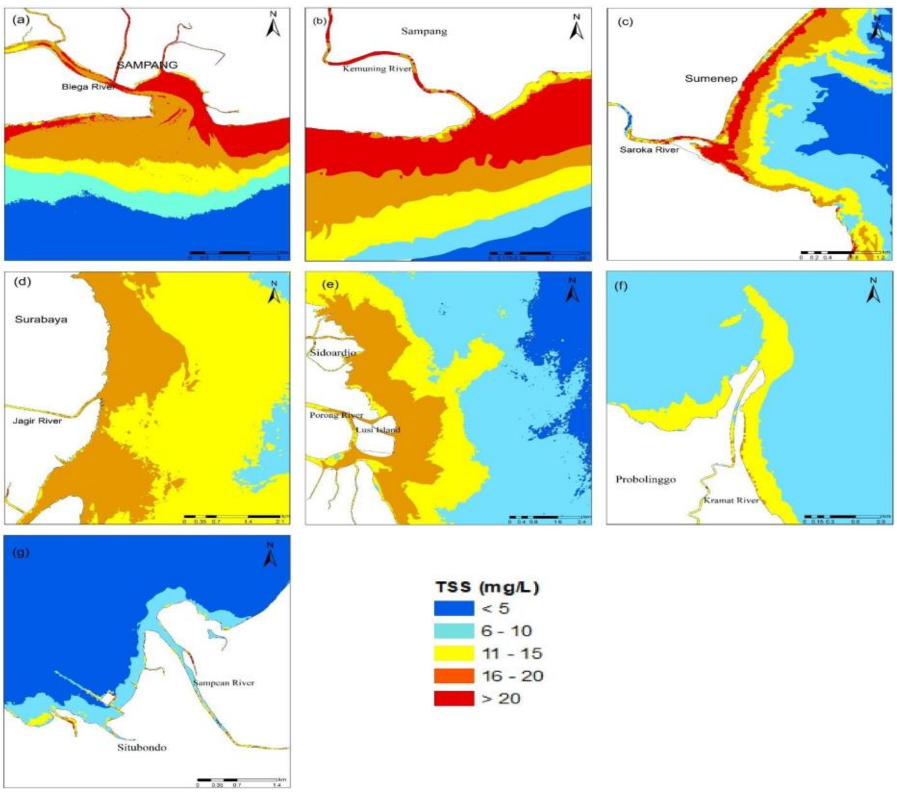

Figure 6. Distribution of total suspended solid in the dry season. a. in the Blega River in Sampang District; b. in the Kemuning River in the Sampang District; c. in the Saroka River in the Sumenep District; d. in the Jagir River in Surabaya City; e. in the Porong River in the Sidoarjo District; f. in the Kramat River in the Probolinggo District; g. in the Sampean River in the Situbondo District

The correlation coefficient of the satellite imagery data with the TSS field data in the dry season was 0.6734 (Figure 4a), and in the rainy season was 0.6511 (Figure 4b). This explains a strong relationship between the TSS values of satellite imagery data and in-situ data in the rainy and dry seasons, with a value range of R^2 = 0.60-0.79 (Sarwono, 2006). So, a model can be built. A new formula for analyzing TSS with satellite imagery has been developed. The formula for TSS algorithm analysis in the dry season was:

$$3.2825 * \left(31.42 * \left(\frac{\text{Log}(\text{RRS2})}{\text{Log}\ (\text{RRS4})}\right) - 12.719\right) - 37.745 \quad (4)$$

and that, in the rainy season, was:

$$11.968 * \left(31.42 * \left(\frac{\text{Log}(\text{RRS2})}{\text{Log}\ (\text{RRS4})}\right) - 12.719\right) - 185.28 \quad (5)$$

With the new detection model, it is known that in the middle of the sea, the Madura Strait has a low TSS concentration ranging from 1-2 mg/L; for the dry season, the coast of the Madura Strait has a concentration ranging from 5-18 mg/L and near the estuary has a higher concentration reaching 24 mg/L, while in the rainy season, the coast of the Madura Strait has a concentration ranging from 11-22 mg/L and near the estuary has a higher concentration reaching 35 mg/L. High concentration TSS in the dry season can spread up to 3.5 km from the estuary, covering an area on the coast of up to 4 km; and in the rainy season, it can spread up to 5 km from the estuary, covering an area on the coast of up to 7.8 km (Figure 5 a2&b2). The further the water mass moves towards the ocean, the TSS concentration will decrease.

The distribution of TSS in the dry season around the mouth of the Blega River is 18-29 mg/L, and TSS can spread up to 3.5 km from the mouth of the river, covering an area of up to 4 km (Figure 6a). The distribution of TSS around the mouth of the Kemuning River is 19-31 mg/L, and TSS can spread up to 1.2 km from the river mouth, with an area of up to 2 km (Figure 6b). The distribution of TSS around the mouth of the Saroka River is 7-31 mg/L, and TSS can spread up to 1 km from the river mouth, with an area reaching1.2 km (Figure 6c). The distribution of TSS aroundthe mouth of the Jagir River is 12-19 mg/L, and TSS can spread up to 1.3 km from the mouth of the river withinan area of 1.5 km (Figure 6d). The distribution of TSS around the mouth of the Porong River is 10-19 mg/L, and TSS can spread up to 1.6 km from the mouth of the river, with an area reaching 2 km (Figure 6e). The distribution of TSS around the mouth of the Kramat River is 11-22 mg/L, and TSS can spread up to 0.8 km from the river mouth within an area of 0.4 km (Figure 6f). The distribution of TSS around the mouth of the Sampean River is 7-29 mg/L, and TSS can spread up to 0.5 km from the mouth of the river within an area of 0.2 km (Figure 6g).

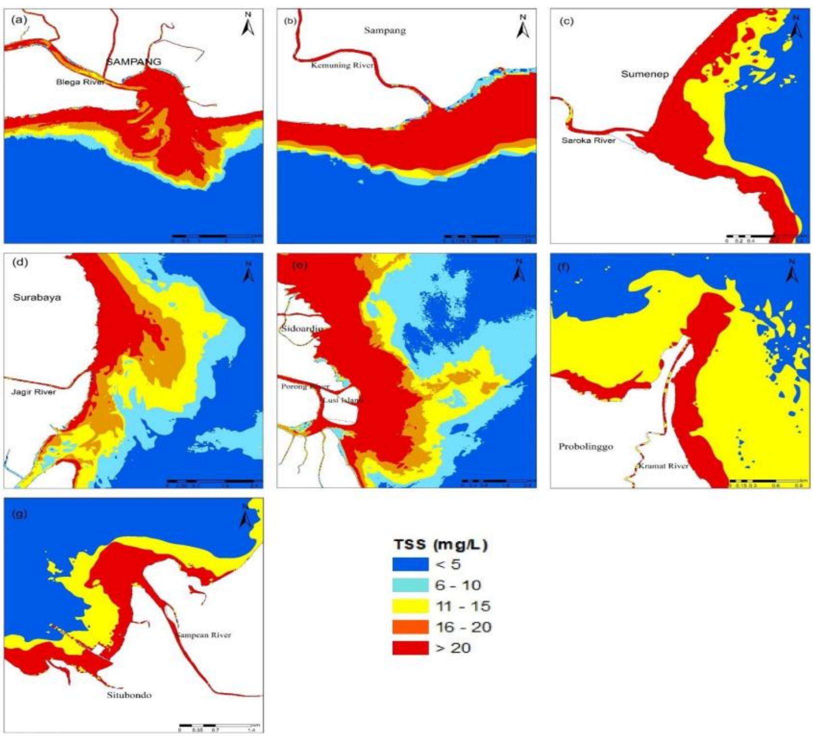

Figure 7. Distribution of total suspended solid in the rainy season. a. in the Blega River in Sampang District; b. in the Kemuning River in the Sampang District; c. in the Saroka River in the Sumenep District; d. in the Jagir River in Surabaya City; e. in the Porong River in the Sidoarjo District; f. in the Kramat River in the Probolinggo District; g. in the Sampean River in the Situbondo District

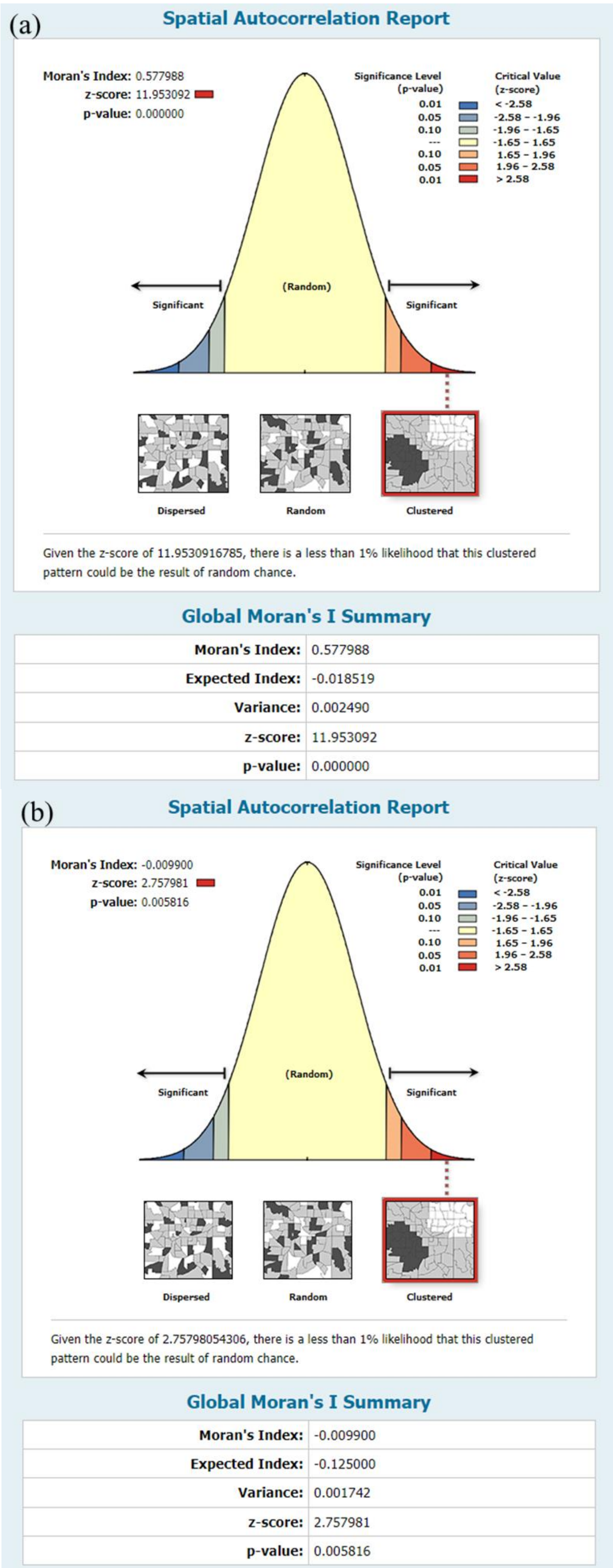

Figure 8. Pattern of total suspended solids using Index Moran. (a) in the dry season and (b) in the rainy season

The distribution of TSS in the rainy season around the mouth of the Blega River is 32-53 mg/L, and TSS can spread up to 5 km from the mouth of the river, covering an area of 7.8 km (Figure 7a). The distribution of TSS around the mouth of the Kemuning River is 32-53 mg/L, and TSS can spread up to 1 km from the river mouth within an area of 1.5 km (Figure 7b). The distribution of TSS around the mouth of the Saroka River is 11-53 mg/L, and TSS can spread up to 1.5 km from the river mouth within an area of 1.6 km (Figure 7c). The distribution of TSS aroundthe mouth of the Jagir River is 22-43 mg/L, and TSS can spread up to 1.5 km from the river mouth, with an area of 1.8 km (Figure 7d). The distribution of TSS around the mouth of the Porong River is 22-43 mg/L, and TSS can spread up to 2.5 km from the river mouth with an area reaching 3.6 km (Figure 7e). The distribution of TSS around the mouth of the Kramat River is 22-43 mg/L and can spread up to 1 km from the river mouth, with an area reaching 0.8 km (Figure 7f). The distribution of TSS around the mouth of the Sampean River is 32-53 mg/L, and TSS can spread up to 1 km from the mouth of the river, with an area reaching 1 km (Figure 7g).

The results of Moran's Index method are H1 hypothesis is accepted so that there is spatial autocorrelation in the distribution of TSS detection. For model dry season (Figure 8a), the Moran's Index value is 0.577988, the value is less than 2.58, the expected value is -0.018519, the variance value is 0.002490, the z-score value is 11.953092, and the p-value is 0.000000. For the model rainy season (Figure 8b), the Moran Index value is -0.009900, this value is less than 2.58, the expected value is -0.125000, the variance value is 0.001742, the z-score value is 2.757981, and the p-value is 0.005816. These parameters are then used for statistical test calculations. It is known that the results of the calculation of H0 are rejected, and H1 is accepted, although the value of the Moran index is negative in the rainy season. Still, the value is close to 0, so the new TSS detection model results for the dry and rainy seasons have positive spatial autocorrelation, and the distribution pattern formed is a Cluster pattern The cluster pattern shows that the data is similar so that the model can describe the dynamics of the data (Saputra et al., 2024). Based on the z-score value, there is less than 1% chance that this clustered pattern could result from random chance, so it has a confidence value of 99% (Wuryandari et al., 2014).

Conclusion

Based on the results, in the dry season, TSS is 5-18 mg/L and can cover an area of up to 4 km; in the rainy season, 5-22 mg/L and TSS can cover an area of up to 7.8 km. The results of Moran's Index reject H0 and accept H1, so distribution pattern formed is a Cluster pattern, and there is less. These results show that the detection model is relatively reasonable and can be used as training data to detect TSS distribution in the Madura Strait in subsequent years or temporally.

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Author Contributions

Conceptualization and data curation, A.M.D.C., A.D., and F.K.; methodology, formal analysis, writing—original draft preparation, and visualization, A.M.D.C.; validation and supervision, A.D. and F.K.; investigation, A.M.D.C., F.K., and A.H.; writing—review and editing, A.M.D.C., A.D., F.K., and A.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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