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Original Article

Modeling Spatial Distribution of Suspended Sediments in Hoa Binh Reservoir Using Sentinel-2 Image and Co-Kriging

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Abstract: Knowledge about the spatial and temporal distributions of total suspended sediments (TSS) play a crucial role in effectively managing pollution and optimizing reservoir operations. This study utilized an *in-situ* dataset of TSS collected from 79 sampling points within the Hoa Binh Reservoir, coupled with Sentinel-2 (S2) satellite imagery acquired on three different dates: 12/07/2023, 19/12/2022, and 15/10/2022 to map the spatial distribution of TSS across the reservoir during these survey dates. By leveraging the correlation between TSS and the spectral ratio of band 3 to band 4 of the S2 images (with a correlation coefficient of 0.90), this band ratio was incorporated as an auxiliary variable to enhance the accuracy of Co-kriging predictions, with a notable improvement in the determination coefficients (R^2) and the standard errors (RMSE), increasing from 0.08-0.46 to 0.90-0.95 and from 0.17-0.61 mg/L to 0.09-0.18 mg/L, respectively. The resulting TSS maps revealed two distinct trends: a) elevated TSS levels were observed near discharge rivers, while lower concentrations were found in the vicinity of the dam; b) TSS during the wet season (averaging at 1.85 mg/L) were higher compared to those in the dry season (averaging at 0.75 mg/L). These findings highlight the efficacy of utilizing S2 satellite imagery as a valuable tool for accurately mapping TSS spatial distribution across the Hoa Binh Reservoir.

Keywords: Modeling, Suspended solids, Hoa Binh Reservoir, Sentinel-2, Co-kriging.

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1. Introduction

Total suspended sediment (TSS) is an aggregation of inorganic and organic elements insoluble in water, formed through the processes of transportation, sediment re-settlement, and the decay of organic matter. TSS directly influences the primary productivity of aquatic ecosystems through the distribution of light scattering in water [1], thereby affecting water transparency and oxygen levels in the aquatic environment. Moreover, the concentration of TSS in water plays a decisive role in determining the quality of the freshwater aquatic ecosystem environment. Reservoirs serve as one of the most critical sources of freshwater supply for human livelihoods, ensuring biodiversity and regulating the ecological environment of surrounding areas. Nevertheless, the spatial and temporal heterogeneity in the distribution of TSS as well as other sedimentation processes within reservoirs have directly impacted the morphodynamics of the reservoir [2, 3]. Over time, reservoirs gradually accumulate suspended substances at different water levels, thereby reducing water storage capacity and effective volume of the reservoir [4]. Therefore, monitoring the spatial and temporal variations of TSS concentration is crucial for the surveillance and management of reservoir water environments.

Hoa Binh Reservoir is one of the two largest artificial reservoirs in northern Vietnam, formed during the construction of the Hoa Binh Hydroelectric Power Plant in Hoa Binh province. With a total capacity of up to 9.5 billion cubic meters, the Hoa Binh Reservoir plays a crucial role not only in supplying primary electricity for the entire Vietnamese power system and flood control for the Red River delta region but also in promoting water transportation for both the upper and lower reaches. Moreover, it serves as a primary water source for aquaculture, industrial production, and irrigation activities in the lower region, including the Red River delta. Additionally, the Hoa Binh Reservoir functions as the principal source of drinking water for the inhabitants of Hanoi, the capital city, and its neighboring regions [5]. However, over time, along with natural changes and the increasing human activities in the Da River basin, the reservoir has experienced environmental fluctuations and a reduction in capacity due to sedimentation processes [6, 7]. In particular, since the operation of the Son La hydroelectric reservoir, these processes have undergone significant changes. These fluctuations have negatively impacted the existence as well as the utilization of the hydroelectric facility for socio-economic purposes. Therefore, controlling and monitoring water quality in general, and specifically monitoring the TSS levels of the Hoa Binh Reservoir, are crucial to ensure the safe and efficient management and operation of the reservoir.

Due to its canyon-like shape, narrowness, and depth, surrounded by high mountain ranges, with a large surface area (approximately 8000 ha) and considerable maximum depth (up to 110 m), traditional TSS monitoring and observation methods such as *in-situ* sampling and laboratory analysis are often time-consuming and costly. Especially, the data collected typically represent only a limited area around the observation point. This leads to a current situation of data deficiency in reservoir management. Meanwhile, globally, the utilization of satellite image data for assessing and monitoring TSS is one of the feasible and promising applications [8], helping overcome the challenges of traditional survey methods. With the advancement of satellite technology and the spatial resolution of free satellites such as Sentinel 2 (S2) (including both Sentinel 2A and Sentinel 2B) reaching up to 10 meters, along with specialized spectral bands for near-infrared regions, has created excellent opportunities for monitoring TSS in inland reservoirs with characteristics such as being long, narrow, and deep, like the Hoa Binh Reservoir. Drawing upon global experiences and the effectiveness of space technology in environmental resource monitoring, this study aims to explore solutions to comprehensively assess the spatial distribution of TSS in Hoa Binh Reservoir water at three survey times: July 12th, 2023, December 19th, 2022, and October 15th, 2022, within the context of limited observation points on the reservoir (7 - 37 points). To achieve this, the study aims to identify supplementary data from S2 satellite images acquired on the reservoir's surface on the survey dates to enhance the accuracy of TSS estimation within the spatial domain of the Co-kriging model. The research findings will provide essential scientific information and evidence for the effective monitoring and management of the water resources of the Hoa Binh Reservoir.

2. Materials and Methods

2.1. Water Sampling and Measurement

A total of 79 measurement results from survey points at Hoa Binh Reservoir on October 15th, 2022, December 19th, 2022, and July 12th, 2023, were collected. All survey campaigns were conducted on the same days as the S2 satellite acquired images of the Hoa Binh Reservoir area. At each survey point, we conducted measurements of Secchi disk depth (SD), water sampling, and GPS positioning (Figure 1). Specifically, water clarity was measured using a standard Secchi disk (Model 58-B10) with a diameter of 20 cm from the Wildco company (USA), following the method proposed by Lind [9]. Water samples were collected at depth of 30-50 cm below the surface of the water and simultaneously transferred into tightly sealed plastic bottles, kept cool, and subsequently transported to the laboratory for analysis to determine the TSS concentration.

In laboratory, The TSS concentration was determined based on the standard method of APHA [10]. The water samples were filtered through Whatman 1825-047 GF/F glass fiber filters (pore size 0.7 µm, diameter 47 mm). Then, the filters were weighed before and after drying in an oven (KD400, Nuve, Akyurt, Turkey) at 104 ± 1 °C for at least one hour. The TSS concentration will then be calculated using the following equation:

$$TSS = \frac{W_1 - W_2}{V}$$

where TSS units in mg/L. W_1 and W_2 were the weight of the filters before and after filtration which units in milligram (mg). V is the filtered volume of water sample which units in liter (L).

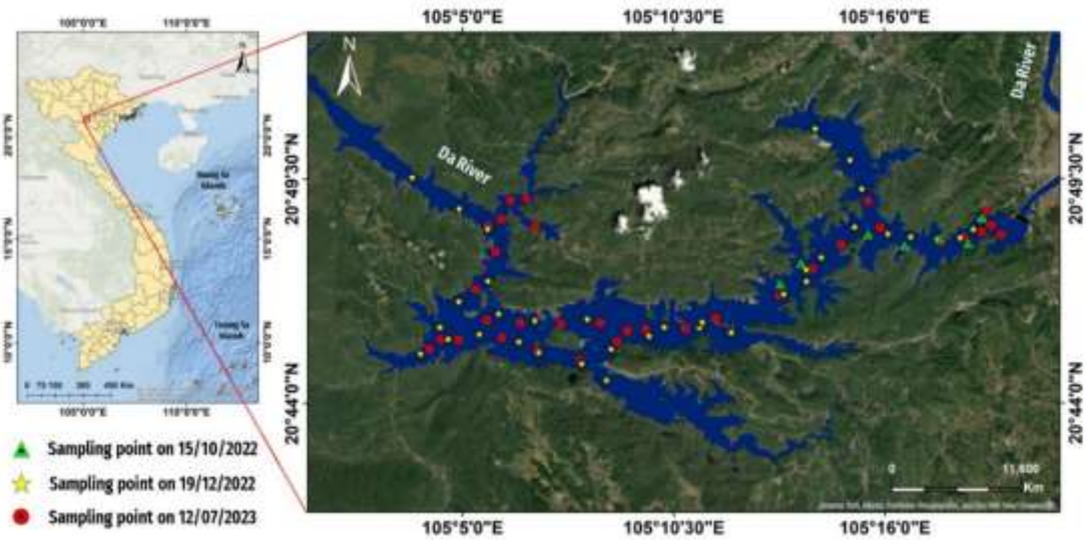

Figure 1. Location of Hoa Binh Reservoir and water sampling points over the reservoir water on three surveyed dates.

2.2. Sentinel-2 Image Processing

The S2 satellite captured images of the Hoa Binh Reservoir area at approximately 3:20 GMT (equivalent to 10:20 local time) in the WGS84 coordinate system, zone 48N, with spatial resolutions of 10 m, 30 m, and 60 m (Table 1). In this study, three S2 images obtained on October 15th, 2022, December 19th, 2022, and July 12th, 2023, downloaded freely from the ESA website (https://scihub.copernicus.eu/dhus/), were utilized (Table 2).

Table 1. Band parameter information for Sentinel-2

S2 Bands (Spatial Resolution)	Central Wavelength (nm)	Bandwidth (nm)
Band 1 (60 m)	443 (Deep blue)	20
Band 2 (10 m)	490 (Blue)	65
Band 3 (10 m)	560 (Green)	35
Band 4 (10 m)	665 (Red)	30
Band 5 (20 m)	705 (Red-edge)	15
Band 6 (20 m)	740 (Red-edge)	15
Band 7 (20 m)	783 (Red-edge)	20
Band 8 (10 m)	842 (NIR)	115
Band 8A (20 m)	865 (NIR)	20
Band 9 (60 m)	945 (NIR)	20
Band 10 (60 m)	1375 (SWIR)	30
Band 11 (20 m)	1610 (SWIR)	90
Band 12 (20 m)	2190 (SWIR)	180

Table 2. Information of Sentinel-2 images used in this study

No.	Scene Identifier	Acquisition Date
1	S2A_MSIL2A_20221015T032721_N0400_R018_T48QWJ_20221015T074856	15/10/2022
2	S2B_MSIL2A_20221219T033139_N0509_R018_T48QWJ_20221219T060245	19/12/2022
3	S2A_MSIL2A_20230712T032521_N0509_R018_T48QWJ_20230712T075600	12/07/2023

All images utilized have undergone radiometric and atmospheric correction to convert the data to Bottom-Of-Atmosphere (BOA) reflectance values by ESA prior to being made available to users. Therefore, in this study, the primary image processing method employed is geometric correction. Accordingly, the images were resampled to a spatial resolution of 10 meters using the Resampling tool in the SNAP (*Sentinel Application Platform*) software to ensure spatial resolution uniformity. Then, the water reflectance at 79 survey points were subsequently extracted and analyzed to determine the variables with high correlation ratios with *in-situ* TSS, which served as parameters for spatial Co-kriging analysis.

2.3. Geostatistical Method

The multivariate geostatistical method of Co-kriging was chosen to establish the spatial distribution map of TSS concentration within the water of the Hoa Binh Reservoir. Co-kriging is a geostatistical technique that utilizes auxiliary variables and considers the correlation information among variables to enhance spatial prediction. Similar to other interpolation methods, this method employs linearly weighted averages; however, their weights depend not only on distance but also on the direction of neighboring data relative to unsampled locations [11]. In this study, the selection of variables in the Co-kriging model must ensure a significant correlation coefficient with *in-situ* TSS values (correlation coefficient greater than 0.70), and the estimation results must have high accuracy (coefficient of determination - R^2 > 0.70; root mean square error - RMSE ≤ 5%). Once this requirement is met, the distribution map of TSS values is established using geostatistical analysis tools in the ArcGIS 10.5 software. Additionally, basic statistical analyses such as determining the maximum value (Max), minimum value (Min), mean value (Mean), and box plots of the data obtained from the survey rounds were conducted using IBM SPSS 26 software.

3. Results

3.1. In-situ Data

The results of TSS and SD obtained within the water of the Hoa Binh Reservoir from the three surveys are depicted in Figure 2. Accordingly, SD values fluctuated from 1.29 m (in July 2023) to 4.6 m (in December 2022), averaging 2.08 m on October 15th, 2022; 3.96 m on December 19th, 2022; and 1.81 m on July 12th, 2023 (Figure 2A). The results of determining the TSS concentration are also relatively consistent with the SD measurement results. The TSS concentration in the lake water ranged from 0.27 mg/L (in December 2022) to 2.86 mg/L (in July 2023), with an average of 0.61 mg/L on October 15th, 2022; 0.78 mg/L on December 19th, 2022; and 1.85 mg/L on July 12th, 2023 (Figure 2B). The correlation between TSS and SD is quite strong, with an R^2 value of 0.7 (Figure 2C). Survey points with low SD values tend to have relatively high TSS concentrations. Compared to other reservoirs in Vietnam such as Tri An Reservoir (Dong Nai, TSS = 3.6 - 9.8 mg/L [12]), Phu Vinh Reservoir (Quang Binh, TSS = 6 - 13 mg/L [13]), or Son La Reservoir (Son La, TSS = 2 - 30 mg/L [14]), the TSS concentration in Hoa Binh Reservoir is significantly lower. The analysis results also clearly indicate the seasonal trend of TSS concentration changes. Specifically, from October to December, which corresponds to the dry season in Hoa Binh, the inflow of sediment-laden water from rivers and streams into the lake is lower than in July. Consequently, there is less suspended sediment input into the reservoir, leading to an increase in water clarity.

Figure 3 illustrates the reflectance spectrum of the water surface of Hoa Binh Reservoir extracted from S2 satellite images at each measurement point. The reflectance spectrum clearly depicts the characteristics of clear water, with the highest reflectance in the green wavelength (B3) and gradually decreasing reflectance as the wavelength shifts towards the near-infrared (NIR) region [15, 16]. Based on the spectral characteristics, single bands and band ratios will be examined to determine their correlation with *in-situ* TSS, thus identifying suitable image information for modeling the distribution of TSS in Hoa Binh Reservoir.

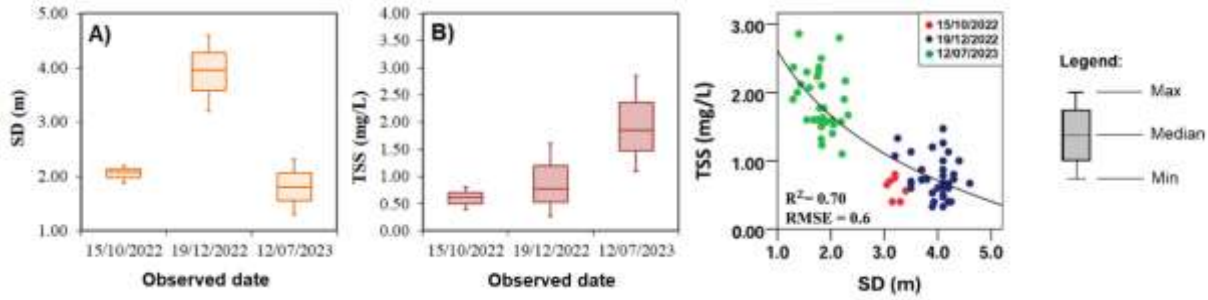

Figure 2. Variation of water clarity (A, SD), TSS concentration (B, TSS) and relationships between SD and TSS (C).

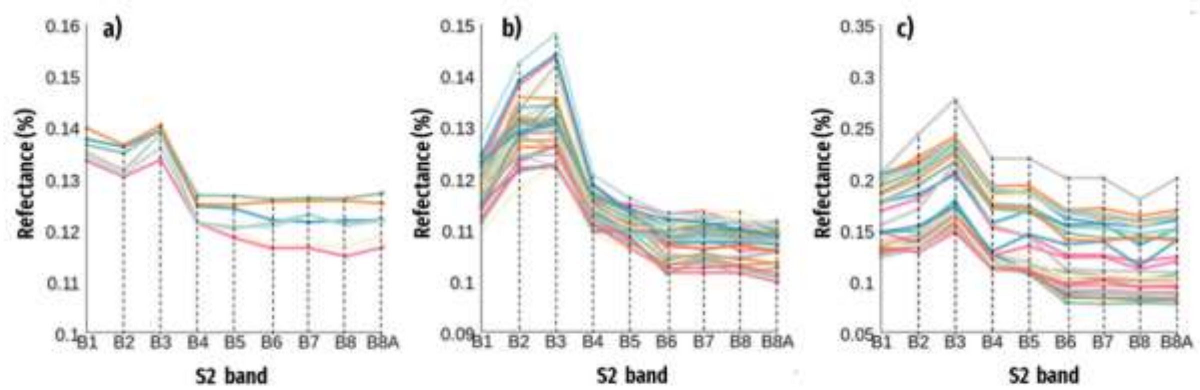

Figure 3. Water surface reflectance spectra extracted from S2 Level-2A pixels corresponding to sampling points on three survey dates: A) on October 15th, 2022; B) on December 19th, 2022; C) on July 12th, 2023. B1 to B8A are S2 bands in the visible and NIR regions.

3.2. Supplementary Information from S2 for Modeling the Distribution of TSS

The utilization of information from satellite images as supplementary parameters for spatial modeling has been employed in several previous studies [17, 18]. Based on the characteristics of satellite images, which provide continuous spatial information in the form of pixels, this method will leverage the correlation between image parameters and the parameters of interest to estimate the values of the parameters of interest at unsampled points. In this study, if *in-situ* measurements are conducted at 30 to 35 points across the entire surface of Hoa Binh Reservoir (with an area of 206 km^2), an estimated 5.9 km^2 would provide input data for the model. Meanwhile, if information from S2 images taken on the same day is utilized, the number of input data for the model could increase to over 4000 points, as there are approximately 4000 image pixels covering the reservoir's surface that meet the quality criteria for TSS estimations. The estimated TSS values at unsampled points across the entire surface of Hoa Binh Reservoir will therefore rely on information from both surveyed points and the remaining image pixels.

The analysis of the correlation between *in-situ* TSS and the single bands of S2 reveals that *in-situ* TSS is not correlated with any single bands of S2 ($r < 0.3$; N = 79). This indicates that no single spectral band can be used as supplementary information for spatial TSS modeling. Band ratios commonly used in estimating TSS concentration, such as the green-to-red ratio, near-infrared-to-red ratio, or green-to-red ratio [8], were also examined. The results show that TSS in Hoa Binh Reservoir is strongly correlated with the green band (B3) to red band (B4) ratio of S2, with a coefficient of determination, $R^2 = 0.81$, and root mean square error, RMSE = 0.29 mg/L (Figure 4).

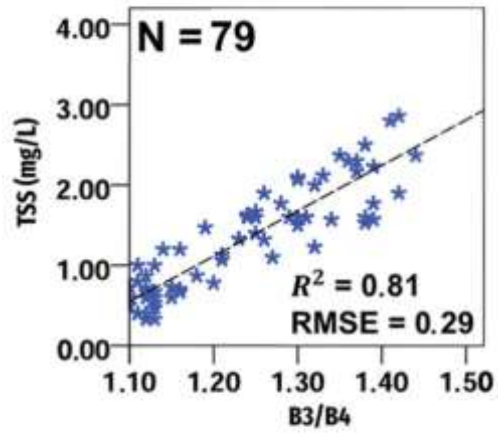

Figure 4. Regression analysis between TSS and reflectance ratio of the green band (B3) versus the red band (B4) of S2 data using 79 points *in-situ* data over the Hoa Binh Reservoir.

These correlation results align well with previous studies on the Red River [19] or Reelfoot Lake [20], indicating that the B3/B4 ratio of S2 images is suitable as supplementary information for modeling the spatial distribution of TSS in the reservoir. The variations of these ratios in the remaining pixels aid in more accurate estimation of TSS values at unsampled points.

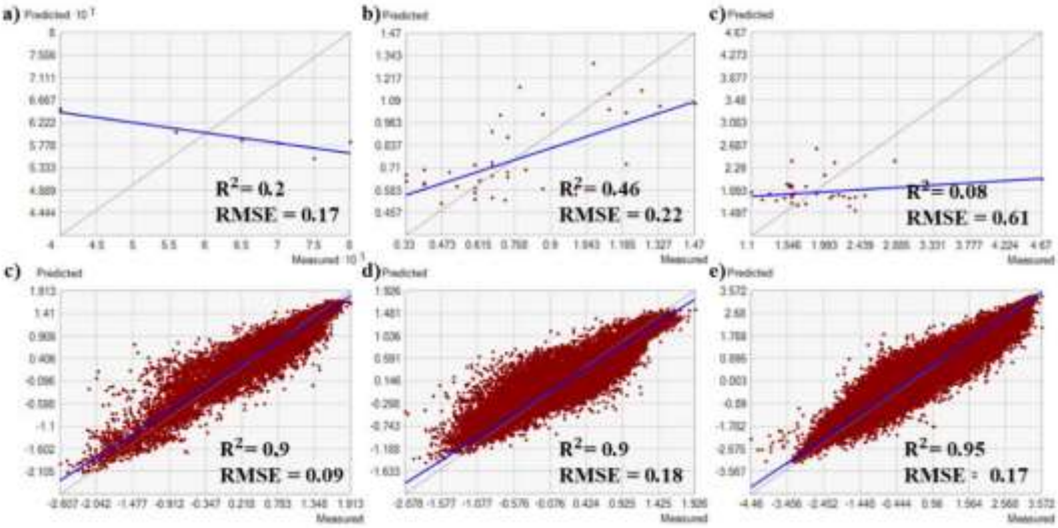

Figure 5. Comparison of the estimated model results using *in-situ* TSS data (a-c) and using a combination of the B3/B4 ratio from S2 imagery and *in-situ* TSS (d-f) across three survey periods.

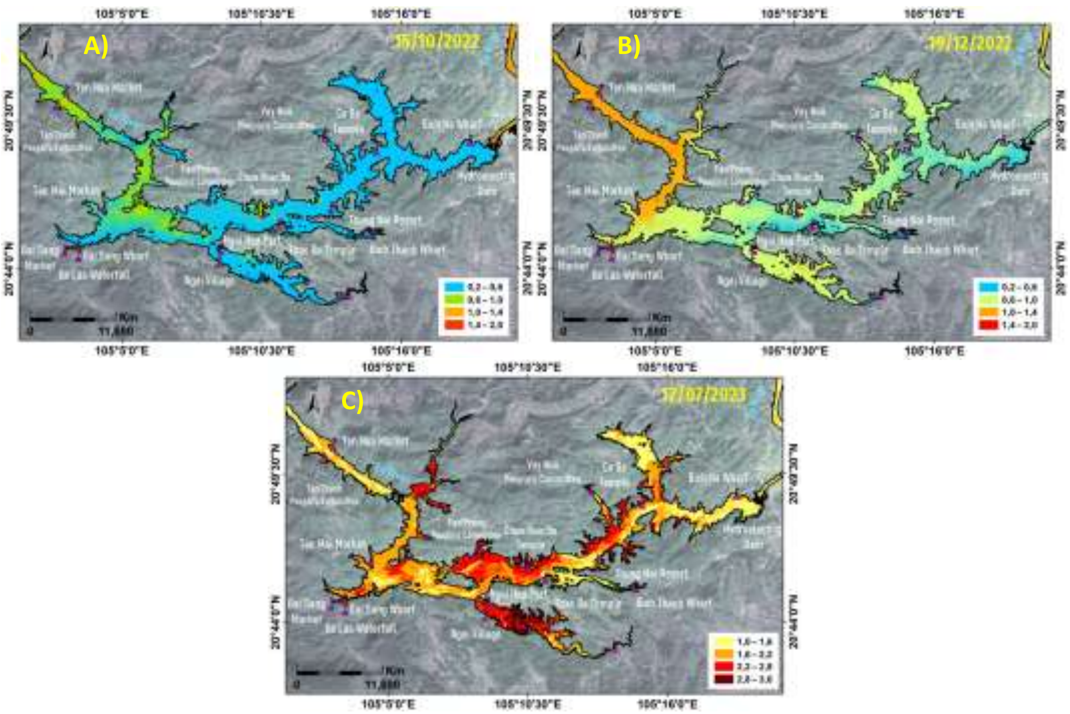

Figure 6. Spatial distribution of TSS across Hoa Binh Reservoir on three measured times: A) on October 15th, 2022; B) on December 19th, 2022; C) on July 12th, 2023.

3.3. Distribution of TSS in Hoa Binh Reservoir in Space and Time

The distributions of TSS are modeled utilizing the correlation between the ratio of band 3 to band 4 of S2 imagery and the *in-situ* data, as depicted in Figure 6. Within the period of October - December 2022, TSS concentration ranged from 0.2 mg/L to 2.0 mg/L, with an average concentration of 0.75 mg/L. Transitioning to July, characterized as the apex of the rainy season, TSS concentrations exhibited a gradual increase albeit not significantly, averaging at 1.85 mg/L. Generally, TSS concentrations are observed to be higher in proximity to river mouths feeding into the reservoir, diminishing towards the dam area. Nonetheless, the spatial distribution of elevated TSS values demonstrates seasonal variability. Specifically, during October - December, heightened TSS concentrations are localized in the vicinity where the Da River discharges into the Hoa Binh reservoir, whereas TSS concentrations in the tributaries and smaller streams surrounding areas such as Vay Nua, Ban Ngoi, and Xom Lanh exceed those of other locations within the reservoir in July. Seasonal fluctuations in TSS distribution further indicate alterations in the contribution of TSS from the tributaries to the Hoa Binh reservoir across different seasons.

4. Conclusion

Accurate modeling of the spatial distribution of TSS is a crucial step in monitoring and managing reservoir water environments. This study utilizes supplementary information from S2 images to enhance the accuracy and detail of the spatial distribution of TSS concentrations in Hoa Binh reservoir. The research findings demonstrate a high correlation between *in-situ* TSS data at 79 points on the reservoir over three dates (October 15th, 2022, December 19th, 2022, and July 12th, 2023) and the ratio of band 3 to band 4 of S2 satellite images (r = 0.81; RMSE = 0.29). This band ratio was then incorporated as an auxiliary variable to enhance the accuracy of Co-kriging predictions. The effectiveness of supplementary information from S2 is evident in the changes in R^2 and RMSE values in the Co-kriging model, where R^2 increases from 0.08-0.46 to 0.90-0.95, and RMSE decreases from 0.17-0.61 mg/L to 0.09-0.18 mg/L. Result maps illustrate two clear trends in TSS distribution in the reservoir water: a) Elevated TSS concentrations are observed in areas proximal to the inflow of river mouths into the reservoir, gradually diminishing towards the vicinity of the dam; b) TSS levels are lower during the dry season (0.75 mg/L) and higher during the rainy season (1.85 mg/L). Spatial TSS distribution aids in identifying TSS sources for the reservoir water. The study also demonstrates the effectiveness of S2 as supplementary information in the Co-kriging geostatistical model for mapping the spatial distribution of TSS, especially when the number of survey points is limited. Future research should expand to collect samples during seasonal transitions to better understand TSS dynamics in the area.

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