Vietnam Journal of Marine Science and Technology; Vol. 21, No. 3; 2021: 271–282
DOI: https://doi.org/10.15625/1859-3097/16076
http://www.vjs.ac.vn/index.php/jmst

Seasonal variation of suspended sediment and its relationship with turbidity in Cam - Nam Trieu estuary, Hai Phong (Vietnam)

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Received: 19 May 2021; Accepted: 23 July 2021

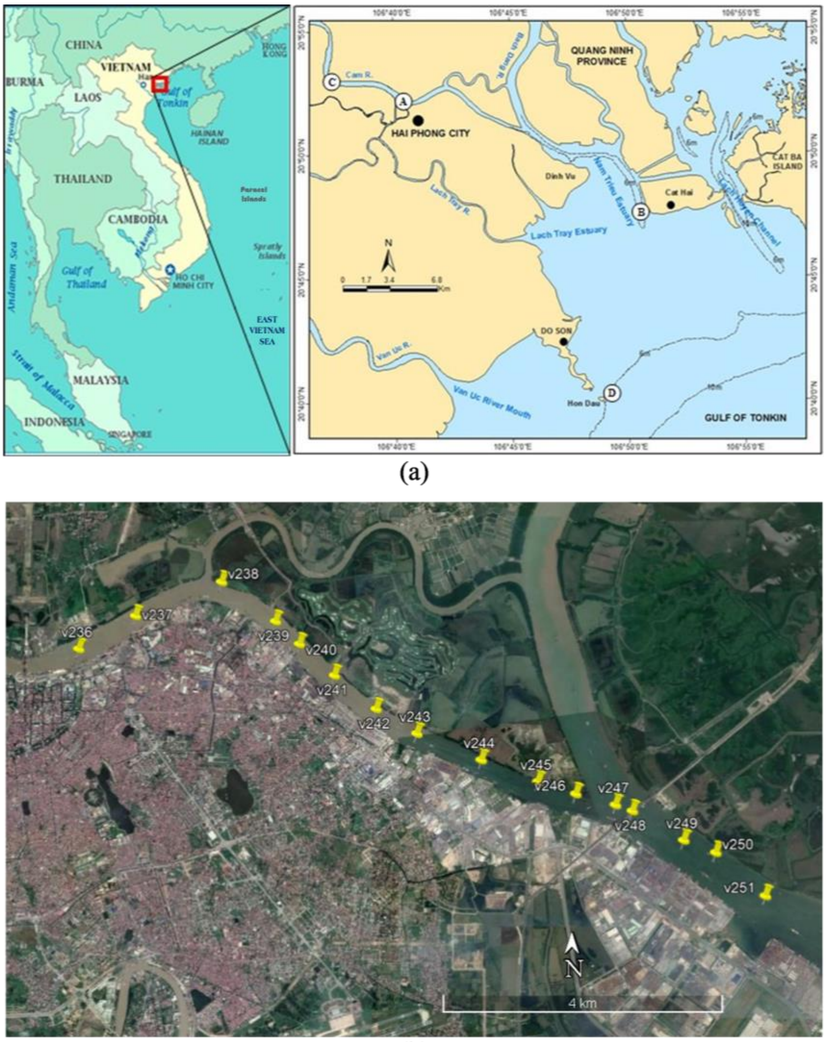
Abstract
We analyzed the seasonal variation of suspended sediment and its relationship with Turbidity in Cam - Nam Trieu estuary based on data measured during three different seasons: Early wet season (May 2015), wet season (September 2015) and dry season (January 2016). The results highlighted the seasonal variation of suspended particle matter (SPM) concentrations with river flow. The average SPM concentration was highest during the dry season, with 62.95 mg/L. They were not significantly different between the early wet and wet seasons, with 59.65 mg/L and 50.94 mg/L, respectively. This study also demonstrated a strong dependence between SPM and Turbidity in the study area. The coefficients of determination varied from 0.867 to 0.971 (linear relationship), and from 0.95 to 0.991 (proportional relationship). Therefore, turbidity can be used to estimate SPM concentration. However, this relationship changed markedly with the seasons, and hence when determining SPM concentration, seasonal factors must be considered.

Keywords: Turbidity, SPM, linear relationship, proportional relationship, Cam - Nam Trieu estuary, Hai Phong (Vietnam).

Citation: Nguyen Minh Hai, Sylvain Ouillon, Vu Duy Vinh, 2021. Seasonal variation of suspended sediment and its relationship with turbidity in Cam - Nam Trieu estuary, Hai Phong (Vietnam). *Vietnam Journal of Marine Science and Technology, 21*(3), 271–282.

INTRODUCTION

Suspended Particulate Matter (SPM) is a significant component of the coastal environment. SPM data gives a better knowledge of sediment transport and the response of the suspended sediment load to resuspension, deposition, and river discharge [1]. In addition, SPM in the water affects the water quality by modifying the light field, as SPM is responsible for most scattering [2]. SPM concentrations are also used as input to hydro-chemical and ecological models [3, 4]. SPM consists of matter kept in suspension in the surface mixed layer by physical forcings, such as currents or wind-wave stirring, and it contains both inorganic and organic material. The inorganic fraction consists mainly of mineral particles originating from river discharge and erosion. The organic part of SPM consists of organic detritus, plankton, and bacteria [2, 5, 6]. The most common and accurate method of measuring suspended solids is by weight. A water sample is filtered, dried and weighed. This method is the most precise technique for measuring total suspended solids; however, it is also more difficult and time-consuming.



(a)

(b)

Figure 1. The Cam - Nam Trieu estuary (a) general location - transects were performed between stations A and B, C is the hydrological station, D is the tide gauge at Hon Dau; (b) example of survey (stations of Transect 3 in Sep 2015) along the A–B transect

Particles and colored dissolved material in water cause turbidity. It can be measured relative to water clarity or directly with a turbidity sensor such as a turbidimeter or a nephelometer. Turbidity is defined as the reduction of transparency of liquids caused by the presence of SPM [7]. Turbidity is a measure of scattering, which is directly related to the concentration of SPM [5, 8]. Thus, turbidity can be used to estimate SPM concentration [2, 5, 9, 10]. An increase in turbidity affects both the top-down and bottom-up processes in ecosystems. Increased turbidity reduces light availability, which may limit primary production [2, 10–12]. Furthermore, it may reduce the nutritional quality of zooplankton, for example, by improving the amount of inorganic suspended particulate matter in comparison to phytoplankton [13, 14]. On the other hand, zooplankton biomass can be positively affected, as increased turbidity reduces the predation success of visual predators [15, 16].

Hydrodynamic activities, such as upwelling events, erosion and anthropogenic causes, such as dredging, can also cause increased SPM load [17]. Hence, SPM concentration and turbidity are essential factors for understanding these processes within the coastal zone. Furthermore, SPM can be used to indicate coastal dynamics and assess the coastal zone's extent [18, 19]. Both SPM concentration and turbidity are essential parameters describing the water quality of natural waters [20]. However, turbidity is more straightforward to measure than SPM by developing the technology to measure turbidity directly. Therefore, set the relationship between SPM and turbidity to retrieve SPM from turbidity data is beneficial [9].

The Cam - Nam Trieu estuary (fig. 1a) is located in Northeast Vietnam and belonging to the Red river delta. This meso- to macrotidal estuary is influenced by a strong seasonal river signal and a monsoon regime; therefore, it is interesting studying sediment dynamics under tropical climate [21]. This area has the most extensive harbor system in the north of Vietnam - the Hai Phong port, which has been affected by increasing siltation. The sediment volume dredged to maintain a minimum depth of the navigation channels was about 0.78×10^6 m^3 in 2013 and 1.17×10^6 m^3 in 2015 with a high induced cost [21, 22]. Hence, many studies such as geomorphology [23], geology [24], hydrodynamics, and sediment transport [25–27] were devoted to find the cause of siltation in the navigation channel deposition and propose solutions.

However, SPM data provided for studying sediment dynamics in this region is always in short supply because it is challenging to measure SPM, especially in the profile of each water column. Therefore, this study aims to provide the relationship between SPM and turbidity along river transects of the Cam - Nam Trieu estuary and information about the seasonal variation of SPM.

MATERIAL AND METHODS

Cam - Nam Trieu estuary

The Cam - Nam Trieu estuary is located in Hai Phong, northeastern Vietnam, which receives water and sediment from the Cam river and the Bach Dang river (figure 1a).

The Cam river is one of two main distributaries (with the Van Uc river) of the Thai Binh river. Although the Cam and Bach Dang rivers belong to the Thai Binh river, they also receive water and sediment from the Red river through the Duong river (see a map of connections within the Red river delta [28]. The total river discharge through the Nam Trieu estuary to the coastal zone is about 20×10^9 m^3year^{-1}, corresponding to 16.5% of the total water discharge from the Red - Thai Binh river system to the Tonkin Gulf [28].

Annually, sediment flux from the Red - Thai Binh river through the Cam and Bach Dang rivers to the coastal zones was about 13.2 $\times 10^6$ t, until the Hoa Binh dam impoundment in the 1980s. From this period, a large amount of riverine sediment has been trapped in the reservoirs. As a result, the sediment flux through the Cam and Bach Dang rivers to the coastal zones decreased to 6.0×10^6 $t.year^{-1}$, in proportion to 17% of the total sediment of the Red - Thai Binh river to the Red river coastal area [28].

The Cam - Nam Trieu estuary is influenced by a tropical monsoon climate with dry winters and wet summers. Annual rainfall in the region (based on measurements at Hon Dau, 1978–2007) was 1,161 mm, of which nearly 83% falls during the summer monsoon (May to October). The wind direction was dominantly (72.2%) from the East (NE, E, SE) and South (SW, S, SE) directions in summer (June to September), and from the North (NE, N, NW) and East (SE, E, NE) directions (92.1%) in the dry season (December to March), from wind data measured at Hon Dau (1960–2011).

Located in the Red river system, the Cam and Bach Dang rivers are strongly affected by their hydrological regime. Based on data from 1960 to 2010, the Red river discharge at Son Tay (near the apex of the Red river delta) varied over the range 80.5 (2010)–160.7 (1971) $\times 10^9$ m^3year^{-1}, with an average value of 110 $\times 10^9$ m^3year^{-1}. Water river discharge encompasses strong seasonal variations, with 71–79% of annual total water discharge in the rainy season and only 9.4–18% during the dry season [28]. Therefore, suspended sediment concentration in regional rivers changes very much by the season, usually about 50–70 mg/L in the dry season and 100–150 mg/L in the wet season. Besides, suspended sediment concentration in the study area is also influenced by hydrodynamics conditions (especially waves), and as well as other human effects (dredging, dumping) [26, 29, 30].

The Cam - Nam Trieu estuary is affected by tides that are mainly diurnal. Based on the tide gauge measurements at Hon Dau station (1960–2011), the tidal amplitude was about 2.6–3.6 m in spring tide and about 0.5–1.0 m in the neap tide.

Field data

Three field surveys were performed in the Cam - Nam Trieu estuary at spring tides during the early wet season (10–13 May 2015), wet season (23–25 September 2015), and dry season (11–12 January 2016). Over these three surveys, 15 transects (6 in the early wet season, 5 in the wet season, and 4 in the dry season) were recorded, including 310 points. Along the river, transects were performed from the upper estuary in the Cam river (position A, fig. 1a) to the Nam Trieu mouth (position B, fig. 1a) or the reverse, in ~ 4–6 hours each. At each station, depth profiles of water temperature, salinity, and turbidity were measured by a *Compact-CTD (ASTD687*, *Alec* Electronics Co. (Nishinomiya, Japan), now released by JFE Advantech Co. (Nishinomiya, Japan) as Rinko-Profiler). In addition, water samples were collected with a Niskin bottle at each station 1.5 m below the surface, from which we measured SPM concentrations and turbidity, measured onboard using a Hach 2100Q turbidimeter.

Data at the hydrographic station of the Cam river (position C, fig. 1a) and data of the National Hydro-Meteorological Service (NHMS) also were used in this study. They include water river discharge (measured every hour) and SPM concentration (averaged values during "flood tide" and "ebb tide" in the sense of decreasing water discharge and increasing water discharge, respectively).

Data processing

SPM concentration was determined by filtering about 100–150 mL per sample through pre-weighed polycarbonate Nuclepore filters (porosity 0.4 μm). Filters were rinsed three times with 5.0 mL of distilled water, dried for 24 h at 75 ^oC in an oven, and then stored in a desiccator until weighing on a high-precision electro balance [21].

The exact process was also applied at selected stations with GF/F filters (porosity 0.7 μm). The sediment concentration after drying 24 h at 75 ^oC provided the total SPM concentration, which includes organic and inorganic matter. After burning the filter at 450 ^oC for two hours, all the organics had been removed, and the particulate inorganic matter (PIM) concentration was measured. The difference between the total SPM and PIM provided the particulate organic matter (POM) concentration and the ratio of organic to inorganic matter within the solid part of the flocs POM/PIM [21]. Based on measured data, we analyzed the relationship of SPM concentration and Turbidity with Microsoft Excel software.

RESULTS

Seasonal various of SPM and Turbidity

Cam - Bach Dang estuary is under the influence of a tropical monsoon climate. Annual rainfall in the region accounted for

90% in the summer, which leads to the highest river discharge in this season. Besides, the instant water discharge at the Cua Cam station is strongly impacted by the tidal oscillation.

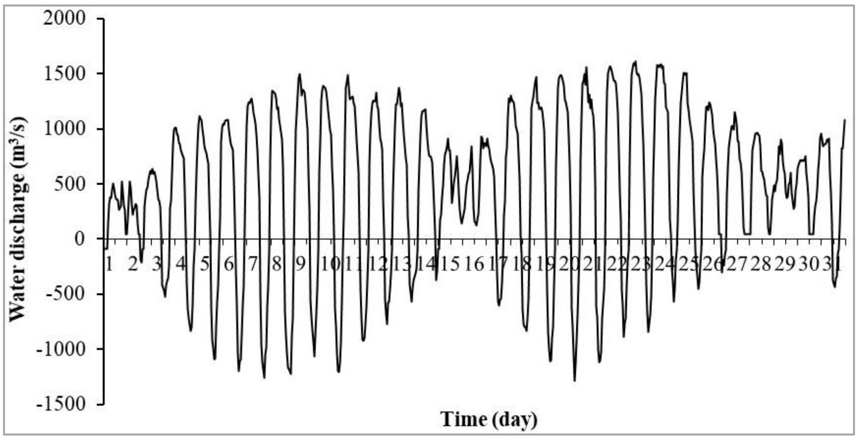


Figure 2. The instant discharge at the Cua Cam station in the early wet season (May 2015)

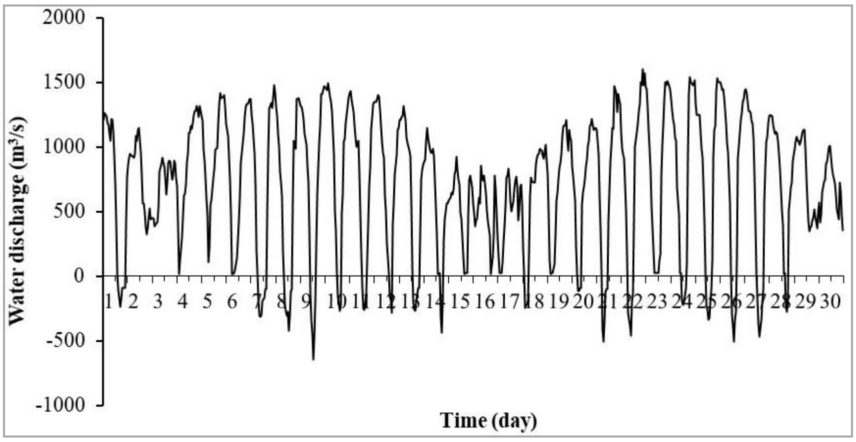


Figure 3. The instant discharge at the Cua Cam station in the wet season (September 2015)

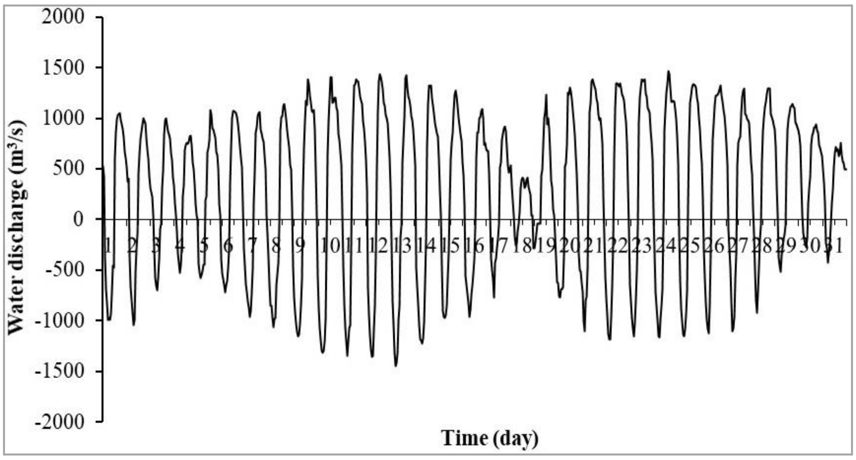


Figure 4. The instant discharge at the Cua Cam station in the dry season (January 2016)

The analysis results from measured data at Cam Station showed that the average river discharge was about 702 m^3/s in the wet season (September 2015), which was 250 m^3/s higher than that of the early wet season (May 2015). The value in the dry season (January 2016) was the lowest, with 284 m^3/s. In the dry season and early wet season, because the river discharges were not high, their distribution was quite balanced during flood tide and ebb tide, especially in the dry season (figs. 2, 3). By contrast, increased freshwater input outweighed tidal influence during the wet season, so river flow was higher than flow from sea to river (figs. 3, 4). While high river discharges occurred in the spring tide, low values were in the neap tide. The highest instant estuarine discharge values were found in the ebb tide (seaward), with about 1,610 m^3/s (in the early wet season and wet season) and 1,470 m^3/s (in the dry season). On the other hand, the lowest value appeared in the floodtide (landward), at 1,450 m^3/s in the dry season, following by 1,290 m^3/s and 640 m^3/s in the early wet season and wet season, respectively.

This study also analyzed the variation of SPM concentration in a month of different seasons (early wet season, wet season and dry season). A graphical presentation of SPM concentration variation versus the river discharge *Q* shows an anticlockwise variation with the lowest concentrations during the rising flood season. Interestingly, the average SPM concentration in the dry season held the first rank (fig. 5), with 62.95 mg/L, 3.3 mg/L higher than that in the early wet season (fig. 6). The average value was the lowest in the wet season, at 50.94 mg/L (figure 7). The highest value of sediment supply from the sea to the estuary during flood tide in the dry season may be explained by a higher tidal pumping induced by a lower freshwater discharge. The SPM had maximum value in the dry season, with 122.5 mg/L, following by 95 mg/L in the early wet season and wet season. The minimum values of SPM appeared in the ebb tide and did not differ markedly among the seasons. The relative variation in SPM, defined as $(SPM_{max} - SPM_{min})/SPM_{mean}$, slightly differed among the three seasons, but maximal value still occurred in the dry season.

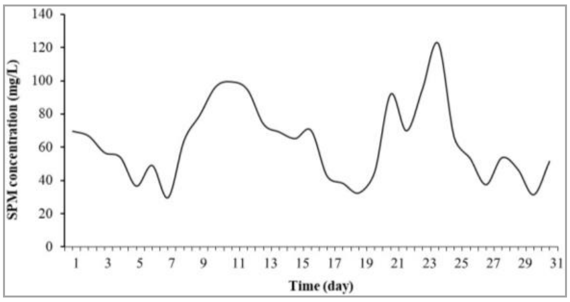


Figure 5. The various SPM concentration (mg/L) in the dry season (January 2016)

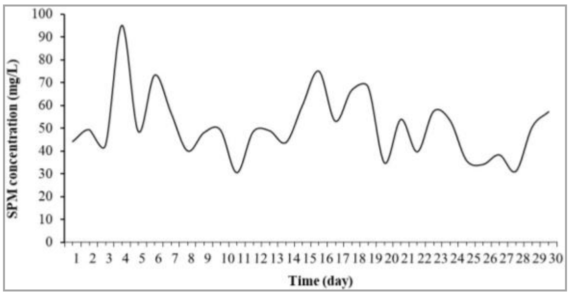


Figure 6. The various SPM concentration (mg/L) in the wet season (September 2015)

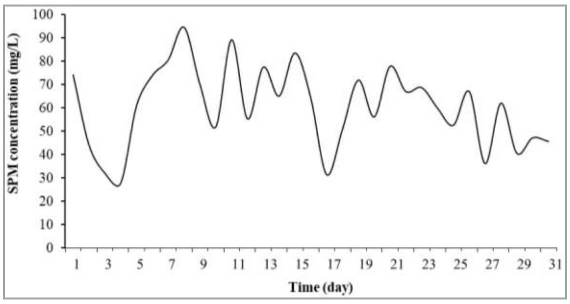


Figure 7. The various SPM concentration (mg/L) in the early wet season (May 2015)

Seasonal variation of the relationship between SPM and Turbidity

A distinct improvement in calculating SPM was observed when using turbidity as the explanatory variable. In the Cam - Nam Trieu estuary, our measurements showed quasi-linear relationships between measured turbidity and SPM concentrations (hereafter determined on polycarbonate Nuclepore filters). In the early wet season, the correlation between turbidity and SPM concentration (with *n* = 23) is shown in figure 8. They showed a good relationship in both linear relationship (figure 8a) and proportional relationship (figure 8b). The coefficient of determination of the proportional relationship (R^2 = 0.991) was higher than linear relationship (linear relationship R^2 = 0.971).

The correlation between turbidity and SPM concentration (with *n* = 44) in the wet season also showed a good relationship in both linear relationship (figure 9a) and proportional relationship (figure 9b). The coefficient of determination of the proportional relationship (R^2 = 0.991) was higher than the linear relationship (linear relationship R^2 = 0.917). Like in the early wet season, the slope of the linear relationship is somewhat higher than the one of the proportional relationship.

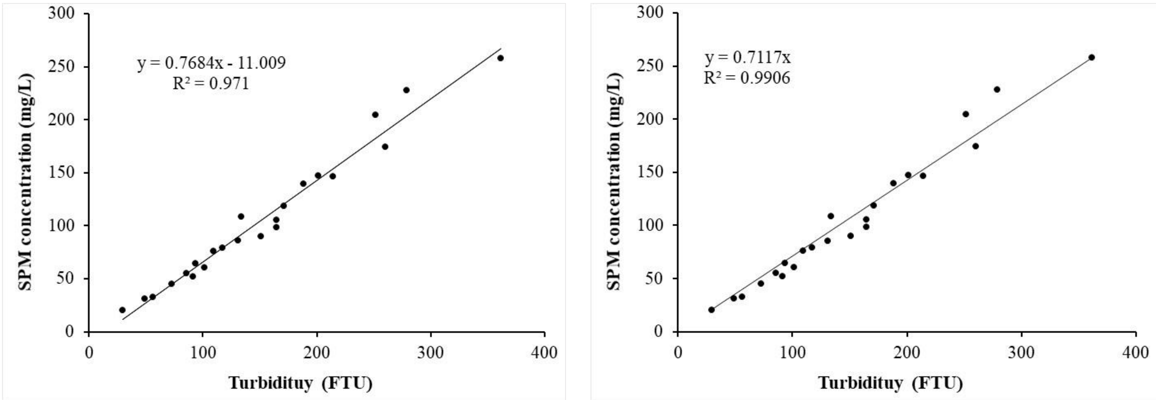


Figure 8. Linear relationship (a) and proportional relationship (b) between SPM and Turbidity in the early wet season

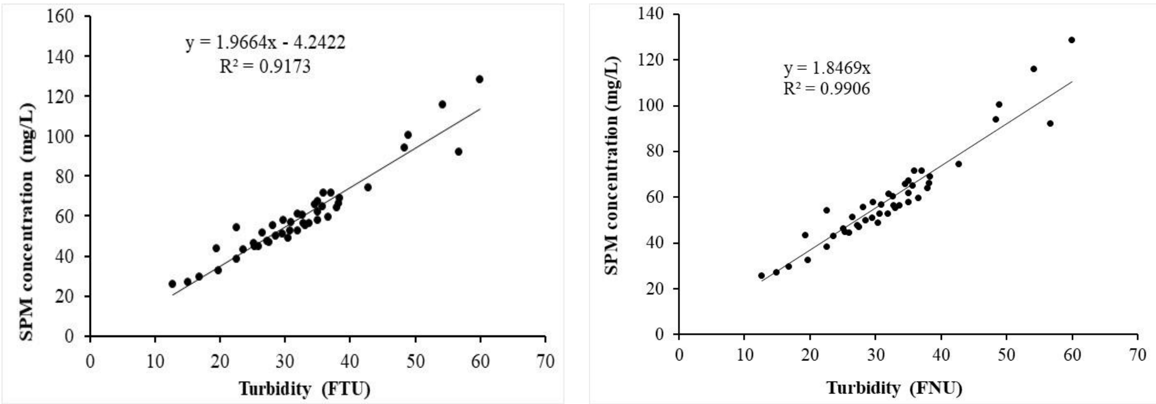
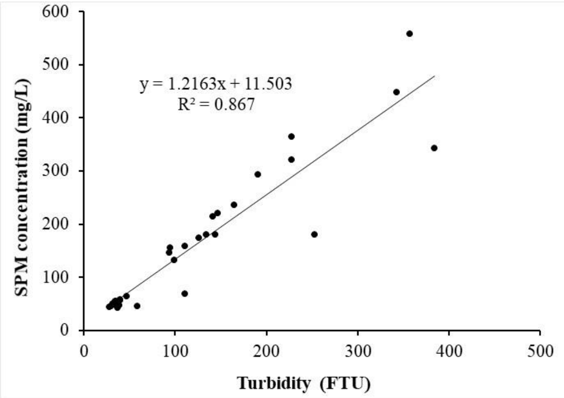


Figure 9. Linear relationship (a) and proportional relationship (b) between SPM and Turbidity in the wet season

In the dry season, the correlation between turbidity and SPM concentration (with *n* = 21) showed a good relationship in both linear relationship (figure 10a) and proportional relationship (figure 10b). The coefficient of determination of the proportional relationship (R^2 = 0.95) was higher than the linear relationship (linear relationship R^2 = 0.867). The slope of the linear relationships between SPM concentration and turbidity in the Cam - Nam Trieu estuary has provided good determination coefficients between turbidity (in FTU) and SPM concentrations (in mgL^{-1}), were used to estimate the SPM profiles from the measured turbidity profiles. The results indicate that turbidity is a strong surrogate for

SSC in the Cam - Nam Trieu estuary. The regression equations demonstrate positive relation. The coefficients of determination varied from 0.867 to 0.971 (linear relationship) and from 0.95 to 0.991 (proportional relationship), which showed a strong dependence between SPM and turbidity in the study area, enabling us to check the good precision and control the quality of measurements.



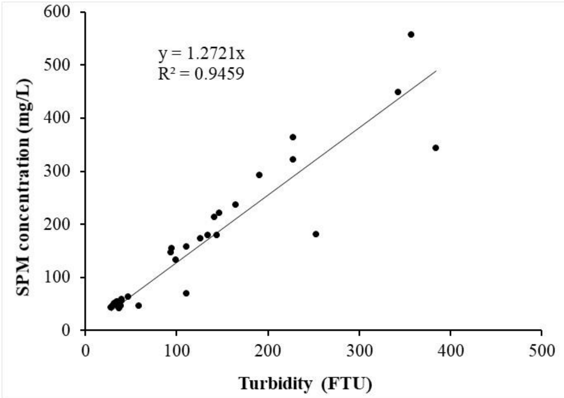


Figure 10. Linear relationship (a) and proportional relationship (b) between SPM and Turbidity in the dry season

DISCUSSION

Usually, in the study area, SPM concentration in the wet season is higher than in the dry season [26, 28]. However, due to dams upstream of the Red river, the difference in SPM concentration of the river waters between seasons is slight. On the other hand, SPM concentration in the Cam - Nam Trieu also depends on hydrodynamic conditions. The previous study in the Cam - Nam Trieu estuary reported wave action in the dry season, cause erosion, which makes increasing SPM concentration [26–29]. On the other hand, Lefebvre et al., (2012) [29] reported that tidal asymmetry generated a pumping of suspended particulate matter upstream during the dry season. As a result, this increases SPM concentration in the dry season in some cases (especially during flood tide). Therefore, SPM concentration at the Cam station in the dry season was higher (in the early wet or wet season).

Many studies have shown a close relationship between SPM concentration and turbidity [9, 31–33]. In this research, the coefficients of determination varied from 0.826 to 0.972 (linear relationship), and from 0.95 to 0.991 (proportional relationship). As a surrogate for sediment concentration, turbidity offers a smart solution, and turbidity meters have been used in laboratory and field situations to estimate sediment concentration [34–37]. Using turbidity values for SPM concentration is an indirect method based on obtaining a statistical relationship between these two parameters, such as linear, non-linear, or polynomial functions [38]. The strong relation between turbidity and SPM concentration has led to turbidimetry being used for continuous monitoring of sediment transportation [37]. The resulting relationships between suspended sediment concentrations and turbidity may be compared to the literature. Yusof (1990) [39] showed the correlation between turbidity and suspended sediment concentration under pre- and post- logging conditions at Pasoh Catchment, Negeri Sembilan. In the study of Christopher (2010) [40], site-specific data were collected from five sites in the Wild Rice River Basin from February 14, 2007, to June 11, 2009. Pearson's correlation test indicated strong positive relations between NTU and SPM concentration (r = 0.96). Besides, Teixeira et al., [41] also assessed the relationship between turbidity and SPM concentration from a small hydrographic basin in Santa Maria (Brazil). Four field measurements were carried out from September

2 to October 6, 2014. The research has resulted in a good correlation between SPM concentration and turbidity (*T*), *r* = 0.8602, (*P* < 0.0001) [41]. Especially a recent study showed that various factors as sediment type, turbidity, salinity, turbulence rate and organic matter are responsible for variations of regression coefficient in the relationship between SPM and turbidity at Cam river [27].

While a relationship between turbidity and suspended sediment concentration can be established, it can change spatially and temporally due to variations in sediment composition and stream energy [42]. The quality of the relationship between turbidity and sediment concentration is crucial in determining the value of the turbidity surrogate. Variations of this relation are related to variations in particle size, shape and composition, instrument stability, lighting conditions, organic load, and biological activity on the probe [43, 44]. Due to the seasonal variation of SPM concentration and turbidity, the relationship between turbidity and SPM concentration will vary accordingly. The correlation between SPM concentration and Turbidity can be compared through slopes and intercepts. In this study, both slope and intercepts have changed by the season. Slopes increase from 0.77 (early wet season) and 1.22 (dry season) to 2.00 (wet season). A lower slope means that the SPM concentration will be lower for given turbidity, and the sensitivity may be lower, while a greater slope means more significant suspended solids for given turbidity [45]. On the other hand, Lefebvre et al., [27], in their research on the seasonal variability of cohesive sediment aggregation, reported that slopes of the relationship between SPM concentration and turbidity at Cam, Bach Dang, and Dinh Vu were higher in the dry season than in the wet season.

In this study, the relationship between SPM concentration and Turbidity was analyzed in both modes, linear and proportional relationship (figures 8–10). Among them, the coefficients of determination of proportional relationship were always higher than the linear relationship. Therefore, both types of relationships should be considered when using these relationships to evaluate SPM concentration from turbidity metrics.

CONCLUSION

Based on survey data in the three different seasons (early season, wet season and dry season), this study showed seasonal variations of SPM concentration in the Cam - Nam Trieu estuary with river flow. SPM concentration was the highest in the dry season, with 62.95 mg/L, contrasting with river discharge. However, they were not significantly different between the early wet and wet seasons, with 59.65 mg/L and 50.94 mg/L, respectively. It is noteworthy that SPM in the dry season is higher than in the wet and transitional seasons, suggesting the effect of bottom erosion in the dry season overweight the influence of the amount of sediment from the continent.

This study demonstrated a strong dependence between SPM and turbidity in the study area. The coefficients of determination varied from 0.867 to 0.971 (linear relationship), and from 0.95 to 0.991 (proportional relationship). Therefore, we can use turbidity data to estimate SPM concentration. However, these relationships changed markedly with the seasons; hence, seasonal factors must be considered when determining SPM concentration.

Acknowledgments: This work was financed by the science and technological cooperation program between the Vietnam Academy of Sciences and Technology (VAST) and the French Institut de Recherche pour le Développement (IRD), the project QTFR01.01/20–21 and NĐT.97.BE/20. This paper contributed to the LOTUS International Joint Laboratory (lotus.usth.edu.vn) and benefited from the support of the VAST05.05/21–22 project.

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