Ocean Systems Engineering, *Vol. 12, No. 4 (2022) 403-411*
https://doi.org/10.12989/ose.2022.12.4.403

Monsoonal sediment transport along the subaqueous Mekong Delta: An analysis of surface sediment grain-size changes

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(Received June 5, 2022, Revised November 9, 2022, Accepted November 28, 2022)

Abstract. Annually, about 48-60% of sediment discharge of the Mekong River is delivered near the mouths of the Mekong River branches which is mostly coinciding with the southwest (SW) monsoon. This sediment budget in turn will be southwestwardly transported along the coast of the Mekong Delta (MD) during the northeast (NE) monsoon. Analysis of monsoonal changes in grain-size distribution (GSD) of surface sediment contributes to a better understanding of erosion and deposition processes along the MD. This study aims to figure out changes in GSD and sediment textures along the MD between SW and NE monsoons based on 183 surficial sediment samples collected along the MD during two field surveys carried-out in October 2016 and February—March 2017. Compared to the GSD during the SW and NE monsoon, the GSD along the MD changed significantly, especially in the estuary areas and along the coast of Bac Lieu and Ganh Hao. Whereas, in the west coast of the MD, GSD seem no changes between the two seasons. These changes in seabed sediment suggest that sediment with grain-sizes ranging from silt to fine sand can be transported during only a NE season.

Keywords: bathymetry; eroding; fine sand; grain-size distribution; Mekong Delta

1. Introduction

The Mekong River (MR) is the eleventh largest river in the world in terms of alluvial sediment discharge with annual suspended load of about 150-170 Mt estimated at the Kratie station in Cambodia (Walling 2008, Wang *et al.* 2011, Milliman and Farnsworth 2011, Milliman and Meade 1983). However, annual alluvial sediment and freshwater discharges from the MR to the lower Mekong River basin has been significantly reduced, especially from the 1990s since the first dam had been built in the mainstream of the upper MR basin (Kummu and Varis 2006, Räsänen *et al.* 2017, Kondolf *et al.* 2014). Recent estimated of suspended sediment discharge of 87.4 Mt/yr by Darby *et al*. (2016) indicates for a significantly reducing in sediment delivery to the lower Mekong Delta basin (in Cambodia and Vietnam) and to coastal areas where it is estimated an annually declining trend of 5% per year of suspended sediment for the period 2003-2012 (Loisel *et al.* 2014). The alarmingly decreasing in discharges from the MR to coastal areas are mainly caused by (1) the construction and operation of hydroelectric dams and irrigation dams in the upper MR basin

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http://www.techno-press.org/?journal=ose&subpage=7 ISSN: 2093-6702 (Print), 2093-677X (Online)

(Kondorf *et al.* 2014, Manh *et al.* 2015) and (2) from sand mining downstream especially in Cambodia and Vietnam (Brunier *et al.* 2014, Besset *et al.* 2019).

Modeled results of Manh *et al.* (2015) show that about 48-60% of annual sediment discharge from the Mekong River (assuming value of 160 Mt/yr) to lower Mekong River basin will be transported to the Vietnamese Mekong Delta mainly during flood season peaking around September-October. These sediment budget, which is mostly deposited to near the mouths of the MR branches, will be resuspended and southwestwardly transported along the coast of the MD during of NE monsoon lasting from November to March (Manh *et al.* 2015, Loisel *et al.* 2014). Averaged values of annual sediment transport along the MD coast from modeled results of Marchesiello *et al.* (2019) show the predominantly transport of sediment from the eastern side of the MD to western side. These sediment transport tendencies could lead to changes in surficial sediment grain-size between the SW and NW seasons. Therefore, identifying seabed sediment grain-size distribution changes over the seasons could contribute to better understanding of erosion and deposition processes along the MD.

Surficial sediment grain-size distributions along the subaqueous Mekong Delta have been studied in some studies which are mostly based on sediment samples collected in several investigation (Liu *et al.* 2017, Szczuciński *et al.* 2013, Unverricht *et al.* 2013, Nguyen *et al.* 2017). Combined surficial sediment samples collected in the surveys in 2007 and 2008, Unverricht *et al.* (2013) created a map of surficial sediment type along the subaqueous Mekong Delta from south of Bassac River mouth in the East Sea to the west sea. Based on these data, Nguyen *et al.* (2017) extended the work of Unverricht *et al.* (2013) to map of seabed sediment cover the entire subaqueous Mekong Delta. By using seismic profiles and sediment samples from cores taken along the coastal area of the Mekong Delta collected during two cruised in 2014 and 2015, Liu *et al.* (2017) analyzed the accumulation and erosion during the geological time periods of a thousand year. However, these seafloor sediment distribution mappings are not considered in changing of surficial sediment grain-size distributions along the subaqueous MD over shorter time scales such as annual or semi-annual time. The main objective of this study is to examine the surficial sediment grain-size distributions in SW and NE seasons along the subaqueous MD. Based on these grain-size data, we identify changes in sediment grain-size distributions between the two seasons and discuss about the processes driving these changes.

2. Materials and method

2.1 Study area

This study is based on the data collected during the two field surveys along the Mekong Delta (Fig. 1) during the highest discharge from the Mekong River to the East Sea at the end of SW monsoon in October 2016 and during NE monsoon in between February and March 2017. Each field survey, about 183 sediment samples were taken on 49 transects from water depths ranging from 1.2 m to 25 m. In addition to the influence of river discharge with its peak around September-November, coastal hydrodynamics of the study area are mainly affected by seasonal wind, wave, and water level fluctuations due to tides with different tidal ranges between eastern and western sides of the MD. The NE monsoon usually lasts from November to March and water level fluctuations due to tides with different tidal ranges between eastern and western sides of the MD.

The NE monsoon usually lasts from November to March during NE with wind and wave directions dominantly are NE or E, whereas the SW monsoon start from May to September showing

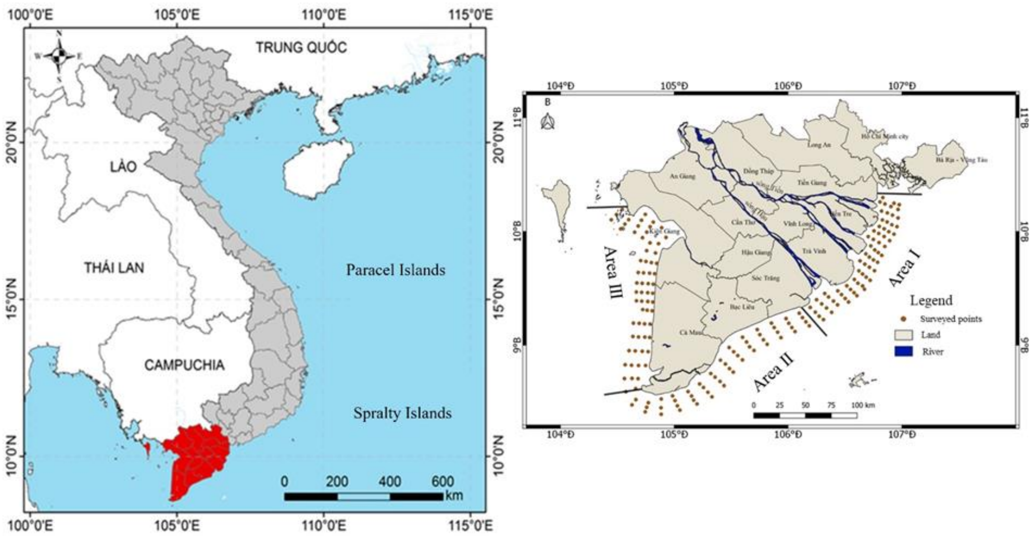

Fig. 1 Map of study and location of sediment samples collected in October 2016 and in February 2017

Table 1 Sediment grain-size classification according to the Vietnam National Standard TCVN 4198-2014

Sediment type		**Grain-size (mm)**
Gravel	coarse	25.4 – 20.0
	medium	20.0 – 10.0
	fine	10.0 – 5.0
	very fine	5.0 – 2.0
Sand	coarse	2.0 – 0.5
	medium	0.5 – 0.25
	fine	0.25 – 0.1
	very fine	0.10 – 0.05
Silt	coarse	0.05 – 0.01
	fine	0.01 – 0.005
Clay		<0.005

wind wave directions are mainly SW (Unverricht *et al.* 2014, Anthony *et al.* 2015). Seasonal wave regimes and coastal currents induced by waves are also changed between the NE and SW seasons resulting the reversal of coastal sediment transport directions between eastern side to western side of the MD. However, on annually average, the amount of sediment from eastern side delivery to western coast of the MD is more significant (Marchesiello *et al.* 2019).

2.2 Grain-size analysis

The grain-size distribution data are obtained from the LMDCZ projects (2018) in which, sediment samples were analyzed for mass distribution of grain-sizes based on the Vietnam national standard (TCVN4198:2014) called “Soils– Laboratory methods for particle size analysis” (Table 1).

Table 2 Shepard sediment classification based on the ratio of gravel, sand, silt, and clay composition (Shepard 1954, O'Malley 2007)

Integer value	Sediment texture	Proportion of Gravel, Sand, Silt and Clay (%)	Sediment type
01	Gravel	Gravel > 50%	unimodal
02	Gravelly sediment	Gravel > 10%	unimodal
03	Sand	Gravel <10%, Sand > 75%	unimodal
04	Silt	Gravel < 10%, Silt > 75%	unimodal
05	Clay	Gravel < 10%, Clay >75%	unimodal
06	Sandy clay	Gravel <10%, Clay >50%, Sand < 50%	bimodal
07	Silty clay	Gravel <10%, Clay >50%, Silt <50%	bimodal
08	Clayey silt	Gravel <10%, Silt > 50%, Clay < 50%	bimodal
09	Sandy silt	Gravel <10%, Silt > 50%, Sand < 50%	bimodal
10	Silty sand	Gravel <10%, Sand > 50%, Silt < 50%	bimodal
11	Clayey sand	Gravel <10%, Sand > 50%, Clay < 50%	bimodal
12	Sand silt clay	Gravel <10%, Clay > 20%, Silt > 20%, Sand > 20%	trimodal

The analysis of sediment samples according to the TCVN4198:2014 is mainly based on sieving for measuring particle sizes larger than 0.05 mm (or very fine sand) and settling tube and hydrometer for estimating particle sizes ranging from silt to clay. For classification of sediment, we apply a Shepard classification (Shepard 1954) which is based on the ratio of gravel, sand, silt, and clays component (O'Malley 2007). Mapping of Shepard sediment classification are obtained based the results of Shepard classification (Table 2) from 183 samples each season using the instruction of O'Malley (2007).

3. Results and discussions

3.1 Sediment grain-size distribution

The results of the seabed sediment distribution representing for the southwest (SW) and northeast (NE) monsoons are presented in Fig. 2 and Table 3. These data show that the sediment types along the subaqueous Mekong Delta are dominantly composed of sand-silt-clay components with grain-sizes of gravel are extremely rare. Therefore, in the ternary graphs of Shepard classification system (Fig. 2), the ratio between gravel, sand and silt elements were not analyzed.

The sediment types in the SW monsoon (during October 2016) show that the compositions of clay, silt and sand components at the three areas (Fig. 1) are very different (Table 3, Fig. 2). Coarser sediment compositions with sand (accounts for 35.8%) and clayey sand (19.4%) types are predominated in the river mouth area (Area 1), whereas finer sediment of silty clay (37.9%) and clayey silt (27.3%) are most composed in the western side of the MD (Area 3). Mixture sediment types but mainly trimodal type (sand silt clay) and bimodal type (silty clay and clayey silt) are found along the eastern coast of the MD (Area 2).

Compared to the data in SW season, sediment compositions and types in NE changed largely

Table 3 Frequency distribution of sediment classification in southwest and northeast seasons grouped for three areas (Area 1: river mouths areas, Area 2: along the eastern coast of the MD toward cape of Ca Mau, Area 3: western coast of the MD, see Fig. 1 for these areas)

Type	Sediment texture	Frequency distribution (%) in Southwest season			Frequency distribution (%) in Northeast season		
		Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
1	Gravel	0	0	0	0	0	0
2	Gravelly sediment	0	0	6.1	0	1.9	10.9
3	Sand	35.8	5.7	0	58.2	5.8	0
4	Silt	0	0	0	0	1.9	0
5	Clay	0	1.9	0	0	0	0
6	Sandy clay	9	1.9	0	0	0	1.6
7	Silty clay	9	13.2	37.9	1.5	0	45.3
8	Clayey silt	4.5	13.2	27.3	13.4	32.7	17.2
9	Sandy silt	4.5	5.7	0	3	1.9	3.1
10	Silty sand	3	3.8	0	3	3.8	3.1
11	Clayey sand	19.4	17	7.6	1.5	9.6	1.6
12	Sand silt clay	14.9	37.7	21.2	19.4	42.3	17.2

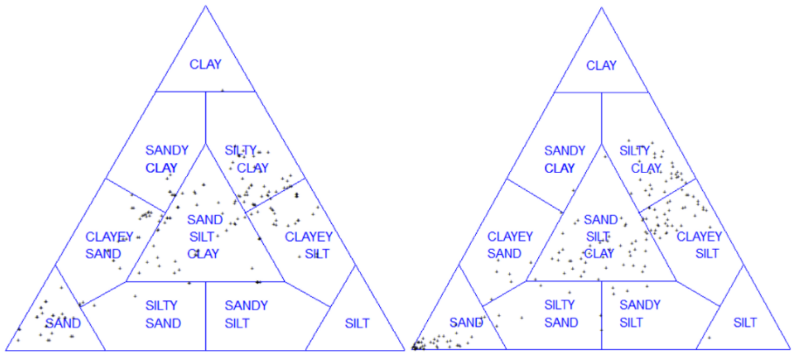

Fig. 2 Ternary graphs of Shepard sand-silt-clay plot of sediment classification in SW (left) and NE (right) seasons

especially along eastern side of the MD (Area 1 and Area 2) (Fig. 2). In Area 1, sand component increases largely from 35.5% in SW to 58.2% in NE (Table 3). In Area 2, the silty clay component was declined (from 13.2% to 0%) but the clayey silt increased (from 13.2% to 32.7%). These changes toward coarser sediment components between SW and NE in Area 1 and Area 2 indicate for the removal of fine-grained sediment during NE season. These fine compositions were possibly transported to the western side of the MD (Area 3) where the composition of silty clay was increased during NE season (Table 3).

It is noteworthy that among the sediment samples obtained, the sediment with unimodal type only appeared as sand (Table 2). Most of sediment samples content mixture sediment compositions but dominantly as bimodal (silty clay, clayey silt or clayey sand). Sediments with 3 components (sand-silt-clay) also account for a very significant proportion.

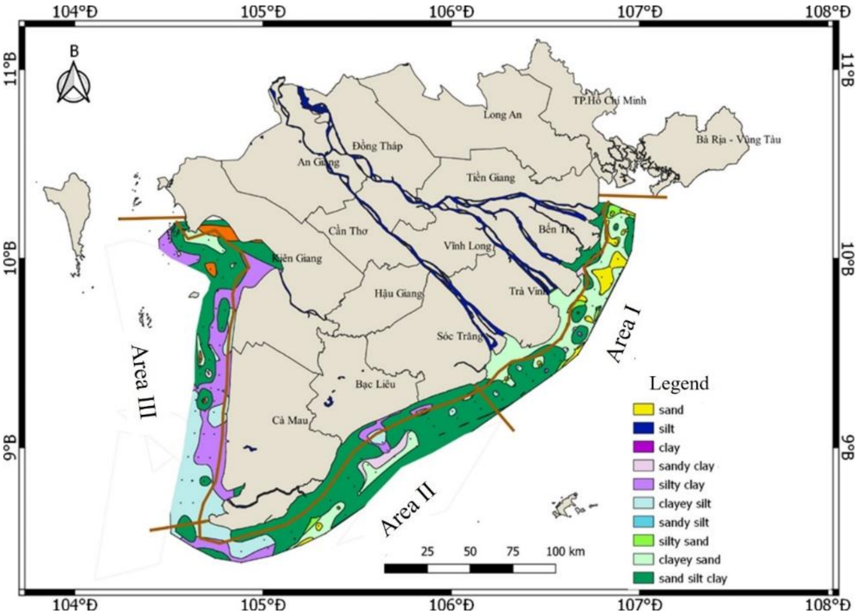

Fig. 3 Map of surficial sediment distribution based on Shepard classification for grain-size distribution in SW season

3.2 Mapping of sediment textures along the subaqueous Mekong Delta

The maps of seabed sediment distribution along the subaqueous Mekong Delta in the Southwest (SW) and Northeast (NE) seasons are shown in Figs. 3 and 4. These maps clearly demonstrate a distinguishingly zoning in the types of sediment with coarser sediment grain-sizes are predominantly distributed in front of the mouths of the Mekong Delta River branches (Area 1, Figs. 1 and 3) and finer sediment grain-sizes are located along the coast from Soc Trang to Ca Mau (Area 2) and in the western side of the MD (Area 3), where sediments are mostly composed of silt and clay. Sediment distribution map for SW season (Fig. 3) show that fine-grained sediment types of mainly sand-silt-clay and clayey sand are predominant in near the mouths of the MR (Area 1) and along the eastern coast of the MD (Area 2).

These fine-grain sediments are possibly delivered to these areas from the Mekong River systems, which have been indicated in the previous studies of Wolanski *et al.* (1996) and Gratiot *et al.* (2017) in which they showed that suspended sediment grain-sizes in a range from fine silt to clay are predominant. Sediment distribution map for NE season (Fig. 4) indicates a largely change in sediment types distributed especially along the Area 1 and Area 2.

The change of sediment type and sediment grain-size between the SW and NE seasons clearly shows the trend of grain distribution to change in a coarser direction in the estuary (Area 1, Fig. 1) and in the coastal areas from Soc Trang to Ca Mau (Area 2) (Fig. 4). These changes imply that that the seasonal sediment transport during NE monsoon is obviously happen during only a season. Finer-grained sediments on the seabed can easily move southwest-west through Ca Mau cape towards the western side of the MD only during an active period of the NE monsoon.

Modeled results of mean annual coastal currents and sediment transport along the coast of the MD given by Marchesiello *et al.* (2019) showed that the predominant tendency of sediment delivery

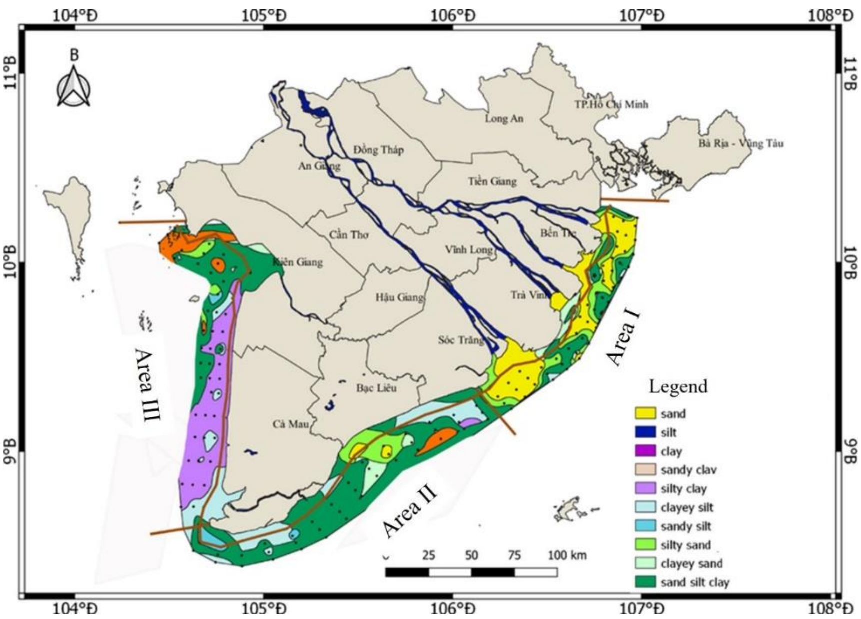

Fig. 4 Map of surficial sediment distribution based on Shepard classification for grain-size distribution in NE season

from east coast to the west coast of the MD. Maps of seabed sediment distribution along the MD in SW and NE seasons demonstrate sediment transport along the coast. These results give evidence to support modeled results of Marchesiello *et al.* (2019). The sediment distribution map in SW season shows the similar pattern of those maps created by Unverricht *et al*. (2013) and Nguyen *et al*. (2017) in which the samples mostly taken during the inter-monsoon in between end of March and April when wave-induced coastal current and sediment transport was lowest. However, the seabed sediment distribution in NE season (Fig. 4) shows a very different pattern compared to the previous maps. Most of changes in sediment grain-sizes and types toward coarser compositions are found in eastern side of the MD especially along the river mouths and the eastern coast from Soc Trang to Ca Mau. These changes indicate for finer grain-size sediment are removed in these areas only during a NE season and are possibly transported over the Ca Mau Cap to the western side of the MD where the sediment types changed from silty clay to clayey silt (Figs. 3 and 4).

4. Conclusions

Seabed sediment distributions along the MD based on sediment samples collected during the periods of SW and NE seasons have been investigated. Changes in grain-sizes and sediment types between SW and NE seasons are strongly found along the eastern side of the MD (Area 1 and Area 2, see Fig. 1). Around the river mouth region (Area 1), fine-grained sediment deposited during high river runoff period were reworked and transported alongshore by NE wave regime. Along the area from Soc Trang to Ca Mau (Area 2) especially around Ganh Hao fine-grained sediment were also replaced by coarser sediment. These changes toward coarser sediment compositions during NE season indicate for coastal sediment transport along eastern coast of the MD are particularly stronger compared to the sediment delivery to the western coast. Therefore, declining sediment discharges from the Mekong River to coastal areas will cause stronger erosion along the eastern coast especially along the coast from Soc Trang to Ca Mau, where highest rates of shoreline erosion have been reported by Anthony *et al.* (2015), Li *et al.* (2017), and Besset *et al.* (2019).

Acknowledgments

This research is funded by Vietnam National University Ho Chi Minh City (VNU-HCM) under grant number C-2020-18-01 project entitled "*Hydrodynamics processes driving the sediment transport along the coast of the Mekong Delta*". In addition, we wish to express our sincere thanks to the anonymous reviewers for their helpful comments, which helped us to improve this draft.

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